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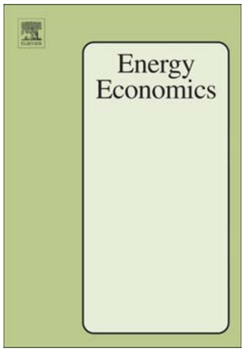

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Revitalising the wind power induced merit order effect to reduce wholesale and retail electricity prices in Australia

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Abstract

This paper investigates the effect of increasing the number of wind turbine generators on wholesale spot prices in the Australian National Electricity Market's (NEM), given the existing transmission grid, from 2014 to 2025. We use a sensitivity analysis to evaluate the effect of five different levels of wind power penetration on prices, ranging from Scenario A, 'no wind', to Scenario E that includes existing and planned wind power sufficient to meet Australia's original 2020 41TWh Large-scale Renewable Energy Target (LRET). We find divergence in prices between states and similar prices for nodes within states. This supports the Garnaut Climate Change Review assessment on the prevalence of 'gold-plating' the intrastate transmission network and underinvesting in interstate connectivity. We find increasing wind power penetration decreases wholesale spot prices but that retail prices have increased in deregulated South Australia and Queensland, similarly, in Victoria. We argue that there is a pressing need to split the large generator-retail companies into separate retail and generator companies and to reassess regulatory rules more generally. Interconnector congestion limits the potential for wind power to further reduce wholesale prices across the NEM. So the need for a high capacity transmission backbone in the NEM is becoming clearer and will become pressing when Australia moves beyond its current 2020 LRET.

Keywords

- Wholesale spot price
- Wind Turbine Generator
- Renewable Energy Planning
- Large-scale Renewable Energy Target
- Interconnector
- NEMLink

Abbreviations

AEMO	Australian Energy Market Operator
AGL	Australian Gas Limited
ARENA	Australian Renewable Energy Agency
LRET	Large-scale Renewable Energy Target
NEM	Australian National Electricity Market

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1 Introduction

In this paper, we investigate causes for the reduction in the merit order effect at higher penetrations of wind power. We suggest ways of removing impediments to the operation of the merit order effect, thus reducing both wholesale and retail electricity prices (Forrest & MacGill 2013; Ketterer 2014). These considerations are also pertinent to understanding the dynamics that have underlain the recent retail electricity price rises in South Australia (SA) (ABC 2016a; Climate Council 2016). We use simulations from the 'Australian National Electricity Market' (ANEM) model (Wild et al. 2015) to assess the effect of five different levels of wind power penetration on wholesale spot prices. These span Scenario, A which represents 'no wind', to Scenario E that includes all the existing and planned wind power sufficient to meet Australia's original 2020 41TWh LRET.

Figure 1 shows the topology of the five states comprising the Australian National Electricity Market (NEM): Queensland (QLD), New South Wales (NSW), South Australia (SA), Tasmania (TAS) and Victoria (VIC). The Australian Capital Territory (ACT) is located within NSW. The number of lines between each state indicates the number of interstate interconnectors. Both the Northern Territory (NT) and Western Australia (WA) have their own independent electricity markets and networks unconnected to the NEM and both are relatively small compared to the NEM.

Figure 1: Topology of the states and interconnectors comprising the National Electricity Market

[Insert]

Australia ranks among the top three countries in the world for solar and wind resources (Drew 2016). The NEM stretches 5,000 km from far north QLD to TAS involving a remarkable geographical spread of wind power (AEMO 2016b). Georgilakis (2008) finds increasing geographic spread increases predictability, reduces variability and minimises near-zero or peak output events. Bell et al. (2015e) have analysed wind speed and electricity demand correlation to determine the ability of WTG to meet electricity demand in the NEM without the aid of energy storage. They found that a lack of correlation of wind speeds between the NEM's peripheral states, including QLD, SA and TAS, was advantageous. Additionally, the correlation between electricity demand and wind speed is strongest between these states. Similarly, they find that the lack of correlation between electricity demands in each of these states yields most advantage.

However, the NEM requires sufficient transmission capacity through VIC and NSW to maximise the benefit of wind power in the peripheral states and the NEM more generally. In this paper we examine price islanding effects that reflect potential transmission constraints through VIC and NSW as well as between other states (Worthington, Kay-Spratley & Higgs 2005). But overcoming these constraints to provide an optimised network structure for the deployment of wind power faces a major coordination problem as the NEM covers seven jurisdictions and contains 25 network service providers (NSP) (AER 2016a). These multiple jurisdictions and NSPs serve only 19 million residents (AEMO 2016b) and present a costly duplication of overheads. In comparison, South Korea has a single combined transmission distribution company serving 51 million residents within a single legislation.

Furthermore, Apergis and Lau (2015) find that there is a high degree of market power exercised by generators in the NEM and this has consequences for prices and mitigating carbon emissions. The Australian generation and retail market is dominated by three privately owned retail-generator companies, AGL, Energy Australia and Origin Energy. These companies are Australia's first, second and third highest emitters of carbon dioxide, respectively (CER 2016), being the owners of large fossil fuel generation fleets. This presents a potential conflict of interest in both the deployment of wind power generation and the augmentation of interconnectors because both reduce the ability of fossil fuel generators to generate at prices above their marginal cost (Spiecker, Vogel & Weber 2013). From the perspective of electricity consumers, one of the key benefits of increased investment in renewable generation is the potential for reductions in wholesale and retail electricity prices as encapsulated by the merit order effect. Once renewable generation projects such as wind farms have been constructed, they are characterised as having very low marginal costs of generation. In a competitive dispatch process based upon marginal costs, and in the absence of transmission branch congestion, wind farms would be expected to be dispatched ahead of thermal generation with higher marginal costs. This would, in turn, lower wholesale electricity prices and retail electricity prices if passed on. A good discussion and overview of the merit-order effect can be found in Felder (2011). The paper is organised as follows. Section 2 presents a detailed literature survey of investigations of the merit-order effect. Section 3 discusses the methodology for the sensitivity analysis and provides an outline of the ANEM model (Wild et al. 2015). Section 4 presents the results of the sensitivity analysis. Section 5 discusses the results and Section 6 concludes the paper.

2 Literature Survey

In general, detailed assessment of the literature identifies three broad methods that have been used to quantify the merit-order effect. These methods are econometric techniques, power flow/unit commitment techniques and agent-based modelling techniques. Of the three methods, econometric techniques dominate, followed by power flow/unit commitment and then agent-based modelling techniques.

There have been a number of investigations of the merit-order effect in Australia. MacGill (2010) identified the role that wind generation had in reducing wholesale prices in SA. Nelson, Simshauser and MacGill (2012) also identified a short-run merit order effect although they also pointed out that high direct capital costs of renewable energy investments also needed to be factored into net economic benefit assessments, particularly in relation to feed-in tariff policy design. Forrest and MacGill (2013) confirmed merit-order effects associated with wind generation in SA and VIC over the period March 2009 to February 2011 using econometric techniques. They found wholesale price reductions relative to median prices of -0.069%/MWh and -0.027%/MWh for SA and VIC respectively. Claudius, Forrest and MacGill (2014) extended these results to the NEM for years 2011-12 and 2012-13 while ignoring potential inter-regional and interconnection effects but accounting for the impact of the carbon price during 2012-13. They estimated the merit-order effect to be -$2.30/MWh and -$3.29/MWh in 2011-12 and 2012-13 respectively. McConnell et al. (2013) demonstrated a merit-order effect associated with scenarios outlining increased penetration of solar PV within the NEM, using a highly aggregated model of the NEM with no generation or transmission constraints. They found potential values of the merit-order effect as a function of installed solar PV capacity between 1 GW and 5 GW to be between $390m and $1229m in 2009 and between $169m and $628m in 2010. They also argued that these estimates were likely to be conservative.

Given the longer history of investment in renewable energy in both the USA and particularly Europe, there is a more significant literature on merit-order effects in international jurisdictions. Given Germany's leading role in promoting investment in renewable energy, it should not be surprising that the greatest amount of investigation have been applied to this particular country. Sensfuss, Ragwitz and Genoese (2008) employed agent-based modelling to calculate a merit-order effect in 2006 of 7.83€/MWh in Germany. They also reported significant variation in merit-order effects over daily cycles with greater effects during peak load periods. Weigt (2009) employed mathematical programming techniques to quantify an average merit-order effect of 10€/MWh associated with German wind power for the period 2006 to the end of June 2008. Keles et al. (2013) investigated the merit-order effect associated with wind power in Germany using a combination of econometric and calibration techniques over the period 2006-2009. They found an average merit-order effect of 5.90€/MWh associated with an average wind power capacity of 4670 MW's. However, for very high wind power penetrations occurring during high demand periods, the merit-order effect could represent as much as a reduction in wholesale prices of 130€/MWh.

Mulder and Scholtens (2013) investigated the merit-order effect of Dutch and German wind power on Dutch wholesale electricity prices. They used wind speed data as a measure of wind power. They found that Dutch wholesale electricity prices were affected more by German wind speeds than Dutch wind speeds. For German wind speeds, they estimated a merit-order effect using econometric techniques over the period 2006-2011 of -0.03 per cent associated with a one percent increase in German wind speeds. Tveten et al. (2013) investigated the merit-order effect associated with increased solar PV electricity production in Germany over the period 2006 to 2011 using econometric techniques. They found that the merit-order effect varied on a year-on-year basis, declining from 7.4€/MWh in 2009 to 3.1€/MWh in 2011. They also found that the increase in solar PV electricity production also reduced the average price variability albeit at a declining trend over the period 2009-2011. Wurzburg, Labandeira and Linares (2013) used econometric methods to estimate a merit-order effect over the period July 2010 to end of June 2012 of 2 per cent of the electricity price associated with the combined impact of wind power in Germany and Austria on day-ahead wholesale electricity prices in Germany and Austria.

Claudius et al. (2014) also investigated the merit-order effects of wind and solar PV in Germany over the period 2008 to 2012 using econometric methods. They estimated a merit-order effect of 6€/MWh in 2010, increasing to 10€/MWh in 2012. Using their estimated relationships, they forecast that the merit-order effect would increase to between 14€/MWh and 16€/MWh by 2016. Ketterer (2014) examined the merit-order effect of wind power in Germany over the January 2006 to January 2012 period using daily day-ahead electricity price data and a GARCH model. The author identified a merit-order effect associated with a one per cent increase in wind power of between 0.1 per cent and 1.46 per cent, depending upon model specification. A decline in the magnitude of the merit-order effect over time was also identified linked to growth in solar PV and trade within Europe. Ederer (2015) also identified a merit-order effect associated with offshore wind in Germany using a simulation approach based on data over 2006 to 2014. Ederer (2015) found that the steadier offshore wind resource imposed less variability on spot market price than was the case with onshore wind power.

Bublitz, Keles and Fichtner (2017) investigated the causes of the observed 38 per cent decline in day-ahead spot prices in Germany over the 2011-2015 period. Both econometric and agent-based modelling techniques were utilised. They found that increased penetration of both on-shore and offshore wind power played a bigger role than expansion in solar PV power in explaining the price decline. However, they also found that depressed coal and carbon prices also contributed as significantly as the increase in wind power. Cebulla and Fichter (2017) investigated the linkages between requirements for flexibility, storage demand when coupled with the increased penetration of variable renewable energy sources. They used different power flow models and the 2010 German power plant portfolio to investigate changes in dispatch (e.g. merit-order of dispatch), storage expansion and utilisation. However, they did not calculate wholesale prices and did not quantify the merit-order effect in terms of reduction in wholesale prices. Kyritsis, Andersson and Serletis (2017) investigated the merit-order effects of both wind and solar PV power on daily day-ahead German spot electricity prices over the period 2010 to 2015. The authors used GARCH econometric techniques. Their main findings related to solar PV power having a larger merit-order effect because of its greater correlation with daily peak-load demand periods. Solar PV power also reduced volatility in the day-ahead spot prices. In contrast, wind power increased price volatility whilst also producing a merit-order effect, albeit, at lower magnitude compared with solar PV. Rintamaki, Siddiqui and Salo (2017) investigated the impact of German wind and solar PV power and Danish wind power on volatility in hourly day-ahead wholesale electricity prices in two different regions of Denmark and Germany. The analysis included cross border power flows between Denmark and Germany and between Germany and France. The authors used econometric techniques to estimate relationships based on hourly data over the period 2010-2014 (for Denmark) and over 2012-2014 for Germany. They found that wind power decreased price volatility in Denmark and increased price volatility in Germany. German solar PV power decreased price volatility.

Spain has also been the focus of considerable investigation. de Miera, de Rio Gonzalez and Vizcaino (2008) used statistical methods to calculate merit-order effects from Spanish wind over the 2005 to January 2007 time period of between 8.6 and 25.1 per cent. Gelabert, Labandeira and Linares (2011) used econometric techniques to estimate a merit-order effect for the period 2005 to 2010 of 3.7 per cent. They found that the magnitude of the merit-order effect was also sensitive to increased penetration of combined cycle gas turbines in the Spanish electricity market over this period. Ciarreta, Paz Espinosa and Pizarro-Irizar (2014) examined the merit-order effect of both wind and solar PV power over the period 2008-2012. They used a computational algorithm to quantify the merit-order effect and produced estimates of average price reductions of between 25€/MWh and 45€/MWh for each year, depending on prevailing weather and market conditions. The merit-order effect is also confirmed in Ballester and Furio (2015) based on econometric techniques applied to Spanish day-ahead wholesale electricity prices over the period 2001 to 2013. These authors also identified an increase in day-ahead wholesale electricity price volatility with increased volatility in renewable energy share of electricity production in Spain. Ciarreta, Paz Espinosa and Pizarro-Irizar (2017) extended existing work on the impact of increased renewable generation in Spain accepting the existence of a merit-order effect as an established ‘stylised’ fact.

In the case of Italy, Clo, Cataldi and Zoppoli (2015) examined the merit-order impact of Italian solar PV and wind power on Italian day-ahead wholesale electricity prices over 2005-2013 using econometric techniques. They found that solar PV and wind power produced an average reduction in wholesale electricity prices of 2.3€/MWh and 4.2€/MWh, respectively. The magnitude of the merit-order effect tended to diminish over time with increased penetration of wind and solar PV electricity production. Gulli and Lo Balbo (2015) also investigated the merit-order effect associated with Italian wind and solar PV electricity production over 2010-2013 using a combination of econometric and simulation methods. These authors distinguished between the conventional merit-order effect derived under the assumption of perfect competition and potential implications arising under imperfect competition. Their main conclusion was that the exercise of market power under imperfect competition could diminish the merit-order relative to the conventional perfect competition definition typically cited in the literature.

For Denmark, Munksgaard and Morthorst (2008) employed statistical methods to quantify the merit-order effects of between 0.1c€/kWh and 0.4c€/kWh associated with Danish wind for the period 2004 to 2006. Jonsson, Pinson and Madsen (2010) used non-parametric regression techniques to estimate the merit-order effects of wind power in Denmark over the period January 2006 to the end of October 2007. The authors found reductions in day-ahead wholesale electricity prices of 40 per cent during the night and 45.5 per cent during the day associated with large wind power production periods. They also found that reductions in day-ahead wholesale electricity prices associated with increased wind power penetration of 36.4 per cent for 40 per cent penetration and 54.5 per cent for an 80 per cent wind power penetration rate.

In relation to other European countries, Denny, O'Mahoney and Lannoye (2017) investigated the merit-order effect of wind power on wholesale electricity prices in Ireland. The authors used both econometric and unit commitment modelling techniques. The econometric analysis was conducted using 2009 hourly data and indicated that an increase of one GWh of wind power led to an average fall in wholesale prices of 3.40€/MWh over 2009. This translated into savings of €44.36 million or 3.76 per cent of total annual dispatch costs. The findings from the unit commitment modelling were comparable, being within 1.4 per cent of the econometric results. Lunackova, Prusa and Janda (2017) investigated the merit-order effect of solar PV and other renewables (mainly wind and hydro) on Czech Republic day-ahead wholesale electricity prices. Econometric methods were used to estimate these relationships based on 2010-2015 spot market data. The authors found that solar PV power actually increased wholesale prices marginally (i.e. a 0.7 per cent increase for a 10 per cent increase in solar PV production), and thus, did not display a conventional merit-order effect. The other renewable energy sources did have a conventional merit-order effect, in the range of -2.5 per cent. The authors attributed this unusual result for solar PV power to the Czech Republic's poor solar resources.

Investigations of the merit-order effect have also been performed for continental North America. MacCormack et al. (2010) demonstrated using both statistical and least cost dispatch modelling, the merit-order effect applicable for different levels of wind power penetration rates in Alberta Canada. Pirnia, Nathwani and Fuller (2011) applied a power flow model to assess the welfare gains from the feed-in tariff proposal introduced in Ontario, Canada. The economic analysis employed in that paper was a long run resource planning model with focus on the period 2007-2027. A key conclusion from the paper was that excessively generous feed-in tariff rates that were not cost reflective of renewable energy costs would not improve social welfare.

Woo et al. (2011) used econometric techniques applied to 15 minute zonal price data for Texas over the period January 2007 to May 2010 to estimate a merit-order effect of between $0.32/MWh and $1.53/MWh for a 100 MWh increase in zonal based wind power generation. The authors also investigated the impact of 10 per cent increase in zonal wind power penetration. They confirmed zonal based merit-order effects of between 2 per cent and 9 per cent and identified increases in zonal price variances of up to 5 per cent. Kaufmann and Vaid (2016) used econometric techniques and data over 2010 to 2012 to identify merit-order effects associated with Massachusetts roof-top solar PV up-take of between $0.26/MWh and $1.86/MWh. Martinez-Anido, Brinkman and Hodge (2016) investigated the merit order effect associated with wind power in the New England power system using a DC power flow model. The magnitude of the merit-order effect depended on the level of wind power penetration and whether wind forecasts were utilised and their accuracy. The magnitude of the merit-order effect was greatest if no wind forecasts were employed in the dispatch modelling, in the range of -8.9 to -24.7 per cent depending upon wind power penetration rate. The merit-order effect was of lower magnitude if wind forecasts (with errors) were employed, in the range -1.0 to -5.2 per cent. If perfect wind forecasts were available, the size of the merit-order effect was smaller still, bounded between 0.3 and -2.1 per cent. Woo et al. (2016) examined the merit-order effect in the California day-ahead and real-time markets associated with solar PV and wind power using econometric techniques and hourly data over the period 12 December 2012 to 30th of April 2015. For an increase of 1000 MWh of solar PV, they found reductions in day-ahead and real-time wholesale electricity prices of between $1.9/MWh and $3.2/MWh and $1.0/MWh and $3.7/MWh, respectively. In the case of an increase of 1000MWh of wind power, the equivalent ranges were between $1.4/MWh and $3.4/MWh and $1.5/MWh and $11.4/MWh.

Thus, the above literature survey confirms the existence of a merit-order effect from a multitude of studies across many different countries and utilising different methods of analysis including econometrics, power flow/unit commitment and agent-based modelling.

3 Methodology: a sensitivity analysis using five levels of wind penetration

The ANEM model (Wild et al. 2015) is a sophisticated model of the Australia National Electricity Market (NEM) used to analyse the sensitivity of the NEM to various effects such as climate change (Foster et al. 2013), carbon pricing (Wild, Bell & Foster 2014; Wild, Foster & Bell 2015) and the deployment of solar PV (Foster et al. 2011). In this paper, we investigate the sensitivity of the NEM's wholesale spot prices to increasing levels of wind power penetration. Wild et al. (2015) provides a detailed description of the ANEM model (Wild et al. 2015), justification for the five levels of wind power penetration and the incrementing of the electricity demand profiles of the three baseline years 2010 to 2012 to form three demand projections from 2014 to 2025. We discuss below (1) a brief outline of the ANEM model (Wild et al. 2015), (2) the five levels of wind penetration and (3) the demand profiles before presenting the results in next section.

3.1 Australian National Electricity Market Model

The ANEM model (Wild et al. 2015) uses a Direct Current Optimal Power Flow (DC OPF) algorithm based on Sun and Tesfatsion (2007a, 2007b) using Locational Marginal Prices (LMP) or nodal prices. Neuhoff et al. (2013) provide an international review of DC

OPF modelling.

Six core features of the ANEM model (Wild et al. 2015) are:

- a wholesale power market which includes an Independent System Operator (ISO) and demand and supply side agents distributed across the nodes of the transmission grid
- a transmission grid that is an alternating current (AC) grid modelled as a balanced three-phase network
- wholesale market operation using increments of a half-hour
- ISO undertaking daily operation of the transmission grid within a single settlement system consisting of a real time market settled using LMP
- for each half-hour of the day, the ISO determines power commitments and LMP's for the spot market based on generators' supply offers and demand-side bids which are used to settle financially binding contracts; and
- transmission grid congestion in the spot market is managed via the inclusion of congestion components in the LMP.

Five inputs of the ANEM model (Wild et al. 2015) are:

- half hourly electricity "total demand" for 52 nodes in the NEM;
- parameter and constraint values for 68 transmission lines and 330 generators;
- carbon price, which is assumed zero in this paper;
- fossil fuel prices; and
- network topology of nodes, transmission lines and generators.

Five outputs of the ANEM model (Wild et al. 2015) are:

- wholesale spot price at each node (half hourly),
- energy generated by each generator (half hourly),
- energy dispatched by each generator (half hourly),
- power flow on each transmission line (half hourly), and
- carbon dioxide emissions for each generator (daily).

The transmission grid captures the major transmission pathways associated with the 275, 330, 500, 275 and 220 KV transmission branches in QLD, NSW, VIC, SA and TAS, respectively. Key transmission data required for the transmission grid are base voltage in kilovolts (kV), base apparent power in three-phase megavoltamperes (MVA), branch connection and direction of flow information, maximum thermal rating of each transmission branch in megawatts (MW) and transmission branch reactance in ohms (Sun and Tesfatsion, 2007a).

Each generator agent is configured with a production technology with attributes relating to feasible production interval, including minimum stable operating levels, total variable and marginal cost functions and fixed costs. Depending upon plant type, start-up costs might also be incurred. Each generator also faces MW ramping constraints that determine the extent to which real power production levels can be increased or decreased within the half-hourly dispatch horizon. Production levels determined from the ramp up and ramp down constraints must fall within the minimum and maximum thermal MW capacity limits of each generator.

An electric utility that has an obligation to provide electrical power to end-use consumers (residential, commercial or industrial) represent demand-side agents in the model. The demand agents purchase bulk power in the wholesale power market each day in order to service customer demand in a downstream retail market. It is assumed that retail demands exhibit negligible price sensitivity reducing to daily supplied demand profiles (Sun & Tesfatsion 2007b).

Optimal dispatch, wholesale prices and power flows on transmission branches are determined in the ANEM model by the DC OPF algorithm presented in Sun and Tesfatsion (2007a). This algorithm involves representing the DC OPF problem as an augmented strictly convex quadratic programming (SCQP) problem, involving the minimization of a positive definite quadratic form subject to linear equality and inequality constraints. The solution values are the real power injections and branch flows associated with the energy production levels for each generator and voltage angles for each node. Formally, the DC OPF algorithm (Wild et al. 2015) is:

- Minimize Generator-reported total variable cost and nodal angle differences

  $$\sum_{i=1}^{I}\left[A_i P_{G_i} + B_i P_{G_i}^2\right] + \pi\left[\sum_{I_m \in BR}\delta_m^2 + \sum_{km\in BR,\, k\geq 2}\left[\delta_k - \delta_m\right]^2\right]$$, with respect to real-power

  production levels and voltage angles $P_{G_i},\, i=1,...,I;\ \delta_k,\, k=2,...,K,$ subject to:

- Real power balance equality constraint for each node $k=1,...,K$ (with $\delta_1 \equiv 0$):

  $$0 = PLoad_k - PGen_k + PNetInject_k\,,$$

  Where:

  - $PLoad_k = \sum_{j\in J_k} P_{L_j}$, aggregate power take-off at node k
  - $PGen_k = \sum_{i\in I_k} P_{G_i}$, aggregate power injection at node k
  - $PNetInject_k = \sum_{km\ or\ mk\in BR} F_{km}$

- Real power flows on branches connecting nodes ‘k’ and ‘m’:

  $F_{km} = B_{km}\left[\delta_k - \delta_m\right]$ (Sun & Tesfatsion 2007a, Sec. 3.1)

- Real power thermal inequality constraints for each branch $km \in BR$ $k=1,...,K$ (with $\delta_1 \equiv 0$):

  $F_{km} \leq F_{km}^{UN}$, upper bound constraint: normal direction MW branch flow limit

  $F_{km} \geq -F_{km}^{UR}$, lower bound constraint: reverse direction MW branch flow limit

- Real-power production inequality constraints for each Generator $i=1,...,I$:

  $P_{G_i} \geq P_{G_i}^{LR}$, lower bound constraint: lower MW thermal ramping limit

  $P_{G_i} \leq P_{G_i}^{UR}$ upper bound constraint: upper MW thermal ramping limit, where

$P^{LR}_{G_i} \geq P^{L}_{G_i}$, lower thermal ramping limit $\geq$ lower thermal MW capacity limit and

$P^{UR}_{G_i} \leq P^{U}_{G_i}$ upper thermal ramping limit $\leq$ upper thermal MW capacity limit

'*U*' = upper limit and '*L*' = lower limit, A_i and B_i are linear and quadratic cost coefficients of the variable cost function of each generator '*i*'. P_{Gi} is real (MW) power production level of generator '*i*'. δ_k and δ_m are the voltage angles at nodes '*k*' and '*m*' (measured in radians). Parameter π is a positive soft penalty weight on the sum of squared voltage angle differences. Variables F^{UN}_{km} and F^{UR}_{km} are the MW thermal limits associated with real power flows in the 'normal' and 'reverse' direction on each connected transmission branch $km \in BR$. Note that the thermal MW limit on a transmission branch can vary with the 'normal' and 'reverse' direction of the power flow on the transmission branch.

The linear equality constraint refers to a nodal balance condition, which requires that, at each node, power take-off (by demand-side agents located at that node) equals power injection (by generators located at that node) and power transfers from other nodes on 'connected' transmission branches. On a node-by-node basis, the shadow price associated with this constraint gives the LMP associated with that node, i.e. regional wholesale electricity spot price. The linear inequality constraints ensure that real power transfers on transmission branches remain within thermal limits and the real power produced by each generator remains within lower and upper thermal limits while also meeting half-hourly ramping production limits.

The ANEM model differs in significant ways from many of the wholesale electricity market models used to model NEM wholesale market impacts. First, the nodal structure of the ANEM model is more disaggregated than the structure of many of the other wholesale market models including in MMA (2006), ROAM (2008, App. A, p. II), SKM and MMA (2011, p. 62) and ACIL Tasman (2011, Sec. B2). Second, the solution algorithm used is very different conceptually from the linear programming algorithms used by many of the other wholesale market models. The ANEM model utilises quadratic programming to minimise both nodal angle differences and generator variable costs subject to network limits on transmission branches and generation. Optimal power flows on transmission branches are determined from optimised nodal angle differences. Accounting for power flows explicitly in the equality constraints of the DC OPF algorithm allows the incorporation of congestion components in regional wholesale spot electricity prices. These congestion components can produce divergence between regional wholesale spot electricity prices associated with transmission congestion. This, in turn, allows direct assessment of transmission branch congestion on regional prices (and merit-order effect) associated with the location of renewable energy projects in weak parts of the transmission network that might be subject to transmission congestion.

In contrast, linear programming algorithms do not explicitly optimise power flows as part of the optimisation process, directly capture the impact of branch congestion on spot prices or account for any impact associated with congestion on intra-state transmission branches. Moreover, intra-state regional spot prices are not typically defined in these models. Finally, within Australia, the linear programming models typically use constraint equations derived by AEMO from external power flow investigations. While these constraint equations are relevant to the current generation structure of the NEM, they are not appropriate for studies investigating significant changes to that structure.

3.2 Five levels of wind penetration

We group existing and planned wind farms into five levels of wind power penetration:

a. No wind generation
b. Operational and under construction
c. Advanced planning *(+all the wind farms above)*
d. Less advanced planning *(+all the wind farms above)*
e. Least advanced planning *(+all the wind farms above)*

Two tables 'List of wind farm WTG by scenario and wind climate proxies' and 'List of summary indicators associated with operational and proposed wind farm included in the study' (Wild et al. 2015, tbls. 4 & 5) provide details of the wind farms within the five groups.

As outlined in (Wild et al. 2015), the wind climatology data used came from the Weather Research & Forecasting Model (WRF 2015). WRF is a "mesoscale numerical weather prediction system" that produces 5-minute interval weather predictions, including wind speed vectors, in the geographical region surrounding the windfarms of interest. The latitude and longitude coordinates of representative clusters of WTGs identified from windfarm layouts in planning approval documents formed the basis of geographical locations for WRF data extraction points within each selected windfarm site. WRF data extraction at these latitude and longitude coordinates related to wind climatology results at 80 meters 'Above Ground Level', taking into account the elevation and nature of the terrain surrounding these coordinates when applying the 80 meters above ground level requirement.

Average wind speeds were calculated from the WRF wind climatology results to form the basis for calculating the MW output of each windfarm. Initial calculations involved determining the MW output for a single representative WTG in a windfarm for each five-minute average wind speed for each consecutive five-minute period for years 2010, 2011 and 2012, respectively. The MW output was read off an appropriate WTG power curve for a given average meters per second (m/s) wind speed value. Because the choice of WTG differed from windfarm to windfarm and even within a single windfarm, different WTG power curves were used to calculate WTG output traces.

Total windfarm output was calculated by aggregating the representative WTG output over the number of WTG's within a windfarm in order to calculate the total average five-minute MW output of the windfarm itself. In performing this, account was taken of whether more than one WTG type was installed at a windfarm.

3.3 Baseline years 2010-12 and projections years 2014-25

We use electricity demand profiles from three calendar years 2010, 2011 and 2012. This reduces the chance of modelling an unrepresentative weather year. Additionally, these weather years provide half-hourly correspondence between electricity demand for each node on the NEM and wind power generated for the five levels of wind power penetration for each node on the NEM. The wind power generated is calculated from half-hourly wind climatology results for the years 2010 to 2012 (Wild et al. 2015).

The demand profiles in the three baseline-years are incremented to form projections for the years 2014 to 2025, making three projections. We simulated the five levels of wind penetration for each projection base year, making fifteen projections in all to allow sensitivity analysis.

Examining the wholesale spot prices on each node from the three baseline years 2010 to 2012 considers the effect of differing annual weather systems on the dynamics of the NEM and the wholesale spot prices. In contrast, the projections years 2014 to 2025 consider the effect of growth in electricity demand on the dynamics of the NEM and wholesale spot prices.

4 Results

This section presents the results, which should be read while viewing the schematic diagrams of the ANEM model (Wild et al. 2015, figs. 1-6). These diagrams relate the node numbers to the topology of the transmission network. Additionally, understanding the dynamics of the changes in wholesale prices induced by the introduction of wind farms is aided by referring to the two tables: 'List of wind farm WTG by scenario and wind climate proxies' and 'List of summary indicators associated with operational and proposed wind farm' in the ANEM model (Wild et al. 2015, tbls. 4 & 5). Bell et al. (2015a, tbl. 2) found congestion on only 14 of the 68 transmission lines in the ANEM Model (Wild et al. 2015). Notably, these 14 congested transmission lines include six of the NEM's eight interstate interconnectors and eight intrastate transmission lines but only three of the intrastate transmission lines exhibited any significant congestion. The congestion on the six interstate interconnectors justifies an interstate comparison of the average wholesale spot prices but reviewing the average wholesale prices for the 52 nodes in the ANEM model is unnecessary because groups of nodes linked by uncongested intrastate transmission lines tend to follow the same price movements in magnitude and pattern. Therefore, identifying these groups of nodes within each state's network both provides an alternative view of transmission congestion and 'Representative State Node' analysis reduces needless repetition. We found the wind power penetration effect was by far the largest, followed by the growth in electricity demand and the smallest being the weather effect (Bell et al. 2015b). Hence, the following presentation focuses on the largest effect but analysing individual nodes allows consideration of the two lesser effects.

We discuss below (1) the identification of 'Representative State Nodes' and 'Unrepresentative State Nodes', (2) analysis of the 'Representative State Nodes', and (3) analysis of the 'Unrepresentative State Nodes' to elicit what dynamics cause their price behaviour to be at odds with the 'Representative State Nodes'.

4.1 Identifying representative and unrepresentative state nodes

Figure 2 shows the QLD average wholesale spot prices by node, by electricity demand growth projections years 2014 and 2025 and by weather baseline years 2010, 2011 and 2012. The average wholesale spot prices fall neatly into four groups Node 7, Node 8, Node 11 and all the other nodes in QLD. Respectively, Node 8 (South West QLD) and Node 11 (Gold Coast) are the QLD terminal nodes for the QNI and DirectLink interconnectors between QLD and NSW. Node 7 (Tarong) only slightly deviates from the 'Representative State Node' unlike Node 8 and 11 whose deviations are more considerable. We repeat the process of identifying representative nodes and unrepresentative nodes for QLD used Figure 2 for the other states in the NEM: NSW, SA, TAS and VIC.

Figure 2: QLD average wholesale spot prices by node by projections years 2014 and 2025 and by weather baseline years 2010, 2011 and 2012

[Insert]

For NSW, the average wholesale spot prices fall neatly into two groups Node 12 (Lismore) and all the other nodes in NSW represented by Node 13 (Armidale). Node 12

(Lismore) and Node 13 (Armidale) are the NSW terminal nodes for the interconnectors DirectLink and QNI, respectively.

For SA, any node could represent the average wholesale spot price of the entire state. Node 35 (South East SA) shows slightly higher prices under certain conditions but is still representative of the state. Node 35 is the terminal node for the Heywood interconnector between SA and VIC.

For TAS, any node could represent the average wholesale spot price of the entire state. Node 50 (Tarraleah) exhibits a slightly lower deviation from the 'Representative State Node'.

For VIC, the average wholesale spot price fall into four groups Node 27 (Murray), Node 28 (Dederang), Node 34 (Regional Victoria) and the remaining Nodes 29 to 33. Nodes 27, 28 and 34 are the VIC terminal nodes for interconnectors between VIC and NSW. Node 34 (Regional Victoria) is also the VIC terminal node for the MurrayLink Interconnector between VIC and SA.

4.2 Representative State Nodes

This section analyses the representative nodes of each state. The 'Representative State Nodes' are those nodes that represent the same average wholesale spot price as most of the nodes in the state. The ability to use representative nodes comes from a price islanding effect where the transmission network within each state has relatively little congestion but many of the interconnectors between states are relatively congested. Section 4.3 analyses the 'Unrepresentative State Nodes'. Figure 3 compares the average wholesale spot price between each of the representative nodes. Table 1 lists the NEM's wind farms by state and Scenario. The rank order by total Annual Production across the Scenarios is NSW, VIC, SA, QLD and TAS. Comparing Figure 3 and Table 1 helps to explain the decrease in average wholesale spot prices. Of particular note in Figure 3 is the large reduction in wholesale prices from Scenario A 'no wind' to Scenario B 'Operational and under construction wind' for SA, VIC and TAS and especially for projection year 2025. Because Scenario A represents the 'no wind' situation and Scenario B, 'operational and under construction wind farms', the large reduction in average wholesale prices in Figure 3 associated with Scenario B relative to Scenario A for these States explicitly demonstrates and quantifies a strong merit order effect associated with wind generation. Moreover, the further falls in wholesale average prices relative to Scenario A for the higher wind power penetration Scenarios C to E further quantifies the impacts of the merit order effect associated with increased wind power penetration. Indeed, without the ability to use the 'no wind' Scenario A as the benchmark scenario for price comparisons, quantification and assessment of the merit order effect would not be possible. The remainder of the section discusses the representative nodes in more detail and the wind farm nodal location within each state to identify any potential contributing factors for the unrepresentative nodes.

Figure 3: The representative nodes for each state in the NEM

[Insert]

Table 1: NEM Wind farms by State and Scenario

[Insert]

Figure 3 shows average wholesale spot price for QLD's representative node, Node 1

(Far North). Section 4.3 discusses QLD's unrepresentative nodes that are Nodes 8 and 11. Comparing Figure 3 and Table 2 shows a high correspondence between reduction in average wholesale spot price and Annual Production (GW) from wind generation. For instance, the largest reduction in prices shown in Scenario D in Figure 3 corresponds with the largest increase in QLD wind generation in Table 2. This outcome again clearly shows the merit order effect of wind generation in operation driving down average wholesale electricity prices. The high degree of nodal price equalisation within QLD reflects the fact that there is little if any congestion on intrastate transmission branches. Apart from Node 8 (South West QLD), this lack of congestion produces a common marginal generation unit within QLD and the observed price equalisation across QLD's Nodes. Table 2 shows that only the Far North (Node 1) and Tarong (Node 7) have wind farms in QLD. Node 1 in the Far North is unlikely to affect the unrepresentative QLD Nodes (Nodes 8 and 11) but a transmission line links Node 8 (South West) and Node 7 (Tarong), so the wind farms on Node 7 could affect the prices on Node 8. In concurrence, Figure 2 shows the prices of Node 7 are slightly lower than those of Node 1 the 'Representative State Node.'

Table 2: QLD Wind farms by Node and Scenario

[Insert]

Figure 3 shows average wholesale spot price for NSW's representative node, Armidale (Node 13). Section 4.3 discusses NSW's unrepresentative node that is Lismore (Node 12). Comparing Figure 3 and Table 3 shows a high correspondence between reduction in average wholesale spot price and Annual Production (GW) from wind generation that is a merit order effect. There is smooth trend towards lower wholesale spot prices for NSW compared to the other states. This smooth trend results from (1) moderate increases in electricity demand from 2014 to 2015 (2) a supply of cheap black coal generation and (3) temporally smooth increase in NSW wind power crowding out more expensive gas and hydro generation. Table 1 shows that NSW has the smoothest temporal increases in wind power from Scenario A to E.

Table 3 shows that seven of the fifteen nodes in NSW have wind farms. This makes the wind farms more spatially dispersed than in QLD. The only unrepresentative Node in NSW is Node 12 (Lismore), which lacks any wind farms, but the adjoining Node 13 (Armidale) has the largest cumulative annual production in NSW across the wind power scenarios. Node 13 also adjoins the Unrepresentative QLD Node 8 (South West QLD) via QNI.

Noteworthy, the NSW Node 26 (Tumut) possess a relatively large amount of wind power, see Table 3, and links NSW to all three 'Unrepresentative VIC Nodes' 27, 28 and 34. The large Silverton Wind farm adjoins Node 26.

Table 3: NSW Wind farms by Node and Scenario

[Insert]

Figure 3 shows average wholesale spot price for the 'Representative SA Node' 37 (Greater Adelaide). However, Node 35 (South East SA) exhibits slightly higher prices under certain conditions. Comparing Figure 3 and Table 4 demonstrates a strong merit order effect by showing a high correspondence between reduction in average wholesale spot price and increases in Annual Production (GW) from wind power. In the states of the NEM, SA has the largest installation of wind power by Annual Production in Scenario B and consequently a large reduction in price from Scenario A to B is seen in Figure 3. SA has cumulative wind farms on five of its seven nodes by Scenario E but over half of this wind power is concentrated at a single node, Node 39 (Mid North).

Table 4: SA Wind farms by Node and Scenario

[Insert]

Figure 3 shows average wholesale spot price for the 'Representative VIC Node 32' Melbourne. Section 4.3 discusses the Unrepresentative VIC Nodes 27, 28 and 34. Comparing Figure 3 and Table 5 shows decreasing returns between reduction in average wholesale spot price and Annual Production (GW) from wind generation. The reduction in wholesale spot prices from Scenario A 'no wind' to Scenario B 'Operational and under construction wind' is particularly evident in Figure 3. VIC has an even installation of wind power throughout Scenarios B, C and D of about 4,000 GW by Annual Production but there are diminishing returns on average spot price reduction.

The Unrepresentative VIC Node 34 (Regional VIC) possesses about half of VIC's cumulative wind power Annual Production for all Scenarios. Node 34 is also at the junction of two low MW capacity interconnectors between VIC and NSW (Line 37 - Tumut-Regional VIC) and between VIC and SA (MurrayLink) and both these interconnectors experience high levels of congestion (Bell et al. 2015a). Section 4.3 discusses further the high concentration of wind farms and interconnectedness of the Unrepresentative VIC Node 34.

Table 5: VIC Wind farms by Node and Scenario

[Insert]

Figure 3 shows average wholesale spot price for the 'Representative TAS Node 42' George Town. Node 50 (Tarraleah) exhibits slightly lower prices in Scenario E. This reflects the additional dispatch of the Cattle Hill Wind Farm in Scenario E.

Comparing Figure 3 and Table 4 show a high correspondence between reduction in average wholesale spot price and Annual Production (GW) from wind generation. TAS in Figure 3 also shows a pronounced reduction in wholesale spot prices from Scenario A to Scenario B. Scenario C in TAS witnesses a reduction in average prices without any additional deployment of wind power. However, Table 1 shows that NSW, VIC and SA, have sizable deployments of wind power in Scenario C and Bell et al. (2015a Sec. 3.2.5) discusses the increase in congestion in BassLink in Scenario C, indicating the importation of power into TAS from VIC.

There is lower average prices in Node 50 (Tarraleah) in Scenario E resulting from a combination of more than doubling the wind power of TAS in Scenario E on Node 50 (see Table 4) and the price islanding effect of congestion on Line 64 (Tarraleah-Waddamana) discussed in Bell et al. (2015a Sec. 3.2.5).

Table 6: TAS Wind farms by Node and Scenario

[Insert]

4.3 Unrepresentative State Nodes

This section analyses the unrepresentative nodes of each state. Those nodes whose average wholesale spot price deviates from the average wholesale spot price exhibited by most of the other nodes in the state. Most of the unrepresentative nodes exist around the interconnectors. Therefore, we analyse these unrepresentative nodes around two interconnector groupings (1) the QNI and DirectLink group and (2) the MurrayLink and NSW-VIC interconnector group.

Figure 4 shows the QNI and DirectLink group with its 'Unrepresentative State Nodes' 8, 11 and 12 coloured red. The price dynamics in this group result from three factors (1) the topology about the QNI and DirectLink interconnectors, (2) the deployment of windfarms in adjacent nodes and (3) the congestion on QNI and DirectLink.

Figure 4: QNI and DirectLink Group
[Insert]

(Source: Wild et al. 2015, figs. 2 & 3)

Figure 4 shows the topology of the QNI and Directlink interconnectors between QLD and NSW. Notably, there is mesh structure connecting the rest of QLD to these interconnectors. In contrast, a single transmission line (Line 16) connects the rest of NSW. Bell et al. (2015a, sec. 3.2.1) discuss the complementary congestion patterns on QNI and DirectLink. The congestion on QNI decreases with increasing wind power because windfarms located in Nodes 7 (Tarong) and 13 (Armidale) can more readily contribute to meeting demand within their respective states requiring less power between QLD and NSW to be transferred on QNI. Figure 5 compares the average wholesale prices of the terminal nodes of the QNI and DirectLink interconnectors. The lower congestion on QNI would also imply a greater tendency towards price equalisation between the terminal nodes of QNI, Nodes 8 and 13. A comparison of prices in Figure 5 shows this convergence but note the average wholesale spot price scale for QLD and NSW differ considerably when making comparisons.

Figure 5: QNI and DirectLink Interconnector terminal Nodes 8, 11, 12 and 13

[Insert]

In contrast to the decrease in congestion on QNI with increases in wind power, the congestion on DirectLink increases with increasing wind power. This reflects increased power flows from wind generation at the Armidale node flowing into QLD via the Lismore node and Directlink. This increased power flow quickly congests DirectLink's small thermal limit. The congestion maintains a significant price divergence between the Gold Coast and the Lismore node shown in Figure 5. It shows the average wholesale price of the Representative QLD Node 1 to benchmark the Unrepresentative QLD Nodes 8 and 11. Relative to the prices of the representative QLD Node 1, the prices of the unrepresentative QLD Node 8 and Node 11 are respectively lower and higher. As discussed above, the prices of the Unrepresentative QLD Node 8 more closely aligns with the prices of the Representative NSW Node 13.

Figure 5 also shows the average wholesale price of the Representative NSW Node 13 to benchmark the Unrepresentative NSW Node 12. Node 12 has some of the lowest prices in the NEM in Scenario A 'no wind'. The increase in wind power induces further price reductions that reinforce Node 12's position as the cheapest node in the NEM. In explanation, DirectLink interconnects Node 12 Lismore in North East (NE) NSW and Node 11 Gold Coast in South East (SE) QLD. SE QLD is a high demand region comprised of the adjoining Nodes 9, 10 and 11. Thus, increasing congestion on DirectLink (Bell et al. 2015a, Sec. 3.2.1) would emerge as cheap wind power seeks to flow from lower demand regions in

NE NSW into the higher demand regions of SE QLD. However, DirectLink's thermal capacity of 180 MW limits the power flow from NSW to QLD, preventing price equalisation between the terminal nodes 11 and 12. The lack of equalisation of prices is supported by (1) the lack of generation located at either terminal node and (2) the lower cost wind generation at Armidale node 13 supplying Node 12 compared with the higher cost coal and gas generation located at the neighbouring nodes of South West QLD and Tarong to SE QLD. Additionally, the growth in demand for projection years 2014 to 2025 is lower for NSW than for QLD that also reinforces the price differential. Exacerbating the situation above was the decommissioning of Swanbank B power station in 2012 that had previously contributed to servicing demand in SE QLD.

In summary, with increasing wind power penetration, QNI's congestion will decrease and DirectLink's congestion will increase. Furthermore, increasing the capacity on DirectLink would increase the prices on Node 12 and decrease the prices on Node 11. So, the prices at these 'Unrepresentative State Nodes' would move closer to their respective 'Representative State Nodes'. Section 5.1 discusses further the QNI-DirectLink group.

Figure 6 shows the topology of the MurrayLink and NSW-VIC interconnector group and its 'Unrepresentative VIC Nodes' 27, 28, 34 coloured red. The congested interconnector Lines 37 and 48 are also coloured red (Bell et al. 2015a, Secs. 3.2.2 & 3.2.4). Important to understanding the price dynamics of this group are three factors (1) the congestion on MurrayLink and NSW-VIC interconnectors (2) the concentration of 50% of VIC's wind power's Annual Energy Production at Node 34 (Regional VIC) by Scenario D, see Table 5, and (3) Node 34 is VIC's terminal node for both MurrayLink and NSW-VIC interconnectors.

Figure 6: MurrayLink and NSW-VIC Interconnector terminal nodes

[Insert]

(Source: Wild et al. 2015, figs. 3, 4 & 5)

Figure 7 benchmarks the average wholesale spot prices for the Unrepresentative VIC Nodes 27, 28 and 34 against the Representative VIC Node 32. Node 34 has slightly higher prices than the Representative Node 32. In comparison, the prices of Nodes 27 and 28 are above and below the prices of the Representative VIC Node 32. The low congestion on the NSW-VIC interconnectors Lines 35 and 36 means prices in the VIC Nodes 27 and 28 will more closely match those prices in the NSW Node 26 (Tumut). However, Node 28 also shares an interconnection with Node 34; consequently, the higher prices at Node 34 induce higher prices at Node 28 than at Node 27. Node 27's prices approximate a linear combination of Node 26 and 28s' prices; Node 28's prices approximate a linear combination of Node 26 and 34s' prices.

Figure 7: Benchmarking Unrepresentative VIC Nodes 27, 28 and 34 with Representative Node 32

[Insert]

Figure 8 shows the average wholesale spot prices on three terminal nodes of the interconnectors MurrayLink and NSW-VIC (Line 37), Nodes 26, 38 and 34 located in NSW, SA and VIC, respectively. Given power generally flows from lower to higher priced nodes, there is sufficient price differences to promote SA and NSW electricity exports to VIC.

Figure 8: MurrayLink and NSW-VIC interconnector nodal price comparison

[Insert]

The transmission network about node 34 (Regional VIC) is fragile, which makes assessment difficult. For instance on MurrayLink, from SA to VIC there is a 132 kV network backbone with a thermal capacity limit of 220 MW's while on line 37 linking NSW to VIC there is a single circuit 220 kV network with a 265 MW thermal capacity. In Regional VIC, there is a combination of single and double circuit 220 kV network backbone that connect from Regional VIC to both the Dederang and Melbourne nodes. Thus the whole network can be characterised as a lower voltage, lower thermal capacity network that, as a result, is more prone to congestion; especially on the MurrayLink and NSW-VIC (Line 37) interconnectors. In contrast, the VIC and NSW intrastate network has a higher voltage 500 kV and 500/330 kV backbone. Section 5.1 discusses further the MurrayLink-NSW-VIC interconnector grouping.

5 Discussion

We have conducted a sensitivity analysis of the effect of increasing the number of WTG on average wholesale spot prices in the NEM from Scenario A that is no WTG to Scenario E that is sufficient WTG to meet the original 2020 41TWh Large-scale Renewable Energy Target. The sensitivity analysis also considered the effect of weather and electricity demand growth on average wholesale spot prices. These factors include (1) a growth in electricity demand using the projection years 2014 and 2025, (2) weather using the baseline years 2010 to 2012. We found the effect of wind power penetration on prices the stronger of the three effects and evidence of the merit order effect (Bell et al. 2015b). These findings are consistent with McConnell et al. (2013) who conducted an historical analysis of the effect of solar PV on wholesale spot prices in the NEM

5.1 Detailed investigation of individual nodes

In Section 4.1, we identify nodes in each state whose average wholesale spot prices can represent most of the other nodes in the state, the 'Representative State Nodes'. We also identify those nodes whose average prices are at odds with most of the other nodes in the state, the 'Unrepresentative State Nodes' being clustered around congested interconnectors. These findings are consistent with high levels of congestion found on most of the interconnectors in Bell et al. (2015a) and Worthington, Kay-Spratley and Higgs (2005). We also find a high correlation between increases in wind power penetration within each state and decreases in the average wholesale spot prices of the 'Representative State Node' within each state, demonstrating the merit order effect associated with increasing wind power penetration. These findings also suggest little intrastate transmission line congestion. Bell et al. (2015a) corroborate this inference.

In Section 4.3, we find all 'Unrepresentative State Nodes' are also terminal nodes for the interconnectors. These 'Unrepresentative State Nodes' form two groups (1) those around the QLD-NSW interconnectors QNI and DirectLink shown in Figure 4 and (2) those about the MurrayLink and NSW-VIC (Tumut-Regional VIC) interconnectors shown in Figure 6.

The QLD-NSW interconnectors, QNI and DirectLink, shown in Figure 4 have an interesting topology that causes the congestion on QNI and DirectLink to act in a complementary pattern. Increases in wind power from Scenario A to E increases the congestion on DirectLink but decreases congestion on QNI (Bell et al. 2015a, fig. 5). The topology that causes this associated behaviour is the single transmission line that links Node 13 (Armidale) to the rest of NSW. In contrast, there is a mesh of Nodes and Lines connecting the rest of QLD to QNI and DirectLink with a minimum of two lines. Compounding this basic congestion pattern are the high concentrations of windfarms on Node 7 (Tarong, QLD) and Node 13 (Armidale, NSW).

Regarding average wholesale prices, Figure 5 shows that Node 12 (Lismore, NSW) experiences the lowest prices in the NEM and these prices turn negative during growth in electricity demand from 2014 to 2025. In comparison, QLD is likely to experience the largest growth in electricity demand and prices in the NEM. The congestion on QNI and particularly DirectLink requires addressing for QLD to benefit from the more abundant wind power and lower wholesale spot price electricity in the other states of the NEM. There are the additional benefits that QLD being both tropical and on the periphery of the NEM, its wind speed and demand are less correlated with the rest of the NEM region. Any congestion solution requires considering the unique topology discussed.

The MurrayLink and NSW-VIC interconnectors and 'Unrepresentative VIC Nodes' group shown in Figure 6 present a much simpler topology dynamic than QNI and DirectLink. However, VIC is the central hub in the NEM shown in Figure 1, so the 'Unrepresentative VIC Nodes' have strategic importance. In particular, the Unrepresentative VIC Node 34 (Regional VIC) links VIC to both SA and NSW via MurrayLink and Tumut-Regional VIC Interconnectors, respectively. This position makes the Unrepresentative VIC Node 34 the most strategic in the NEM. In addition, Node 34 has 50% of VIC's windfarms. Both MurrayLink and NSW-VIC (Line 37) interconnectors show congestion (Bell et al. 2015a, secs. 3.2.2 & 3.2.4). MurrayLink shows increasing congestion with increasing wind power from Scenario A to E from a few percent to over sixty percent. In comparison, the congestion on NSW-VIC interconnector (Line 37) stays at about 50%. Importantly, wind generation currently provides 37% of SA's total generation (AER 2016b, fig. 1.7). MurrayLink's congestion presents a major obstacle to balancing SA's large wind power base. Congestion on NSW-VIC interconnector (line 37) also has the potential to constrain power flows from the large Silverton wind farm near Broken Hill significantly.

The VIC and NSW intrastate transmission backbone has 500 kV and 500/330 kV capacity. In comparison, the interconnectors linking Node 34 to SA and NSW as well as Regional VIC itself has either a single or double circuit 132 or 220 kV network structure. A simple solution is to increase the capacity on both interconnectors and intrastate linkages from Regional VIC to both the Dederang and Melbourne nodes.

5.2 The dynamics underlying South Australia's retail price rises

Wind power reduces average wholesale spot prices but the induced transmission line congestion diminishes returns on investment in wind power and the merit order effect. Ketterer (2014) found that the merit order effect also diminished overtime in Germany but also noted that the initial price volatility associated with the introduction of wind power also diminished overtime. He attributed the decrease in volatility to a combination of better market regulations and improved technology. Similarly, the wind power induced price volatility in SA has also followed the German volatility pattern however negative prices are persisting if not increasing in SA (AEMO 2016a).

The combination of the closure of gas and coal generation, induced by the high penetration of solar PV and wind power generation, have resulted in the loss of generation and associated ramping ability to balance supply and demand within SA. MurrayLink's low thermal capacity prevents SA from importing power from VIC or beyond from generators with high ramping ability. The Australian Broadcasting Company (ABC 2016a) reports that Australia's big three retailers Energy Australia, Origin Energy and AGL are planning domestic price rises for SA citing the closure of the Port Augusta power station in SA and issues around coal and gas supply in SA as reasons. Additionally, Apergis and Lau (2015) discuss how policy uncertainty surrounding climate change mitigation initiatives has caused an over investment in open-cycle gas turbine (OCGT) to minimise the risk associated with investing capital. However, while OCGT is fast-ramping generation, it is also an expensive form of generation. The planned deployment of further wind generation and solar PV in SA will exacerbate the congestion on MurrayLink preventing the import of cheaper fast ramping power from VIC and beyond in the NEM. There is a requirement to address the thermal capacity of MurrayLink and beyond. Remembering Figure 6 showing that the VIC terminal node for MurrayLink has 50% of VIC wind farms and the close proximity of VIC and SA wind farms provides high correlation between their wind speeds, 0.53 in Bell et al. (2015e) and 0.64 in Bannister and Wallace (2011), and their resulting generated power. Hence, there is a requirement to link SA beyond VIC to the whole of the NEM.

AEMO (2010a, 2010b, 2011a, 2011b) proposed a high capacity backbone to the NEM's grid called NEMLink that augments the existing transmission lines to address interstate congestion and significantly enhance transfer capability. The ANEM model (Wild et al. 2015, figs. 1-6) shows the transmission lines augmented in the NEMLink proposal in red. NEMLink includes and eliminates congestion on the following three interconnectors QNI, MurrayLink and Regional VIC-Tumut NSW. AEMO (2010a, 2010b, 2011a, 2011b) conducted a Regulatory Investment Tests for Transmission (RIT-T) for NEMLink that excluded BassLink from the proposed NEMLink augmentation. BassLink, being a HVDC submarine cable interconnector, is the most capital intensive of all augmentations evaluated. However, the RIT-T for the NEMLink also excluded the benefits of accommodating high penetrations of renewable energy. Bell et al. (2015e) performed a wind speed and electricity demand correlation analysis for the NEM to determine WTGs' ability to meet electricity demand without energy storage. They found a lack of correlation between the NEM's peripheral states wind speeds and lack of correlation between the peripheral states' electricity demand but a small correlation between the peripheral states wind speed and electricity demand. NEMLink would enable the NEM to avail itself of the benefits wind power more fully. This will become more valuable as the proportion of electricity from wind power increases towards and beyond the 2020 LRET. Bell et al. (2015c, 2015d) investigate the effect of NEMLink on transmission congestion and wholesale spot prices under the five wind penetration scenarios.

5.3 Victoria retail prices and the merit order effect

Evaluating the efficacy of privatisation and deregulation in VIC is informative because VIC was one of the first states to deregulate, in 2009, and VIC has relatively little renewable energy compared to SA. Additionally, SA only deregulated its retail market in 2013 and as discussed in the previous section SA has recently experienced major retail price rises attributed to a combination of high gas prices, inadequate interconnector capacity for the penetration renewable energy and generators manipulating the wholesale spot market prices (ABC 2016a; Climate Council 2016).

The management of some electricity retail companies promote VIC as a successful trial in deregulation and privatisation. However, ABC (2015) reports VIC's retail electricity prices rose 212% between 2008 and 2015, attributing most of the rise to increases in retail margins(ABC 2016a). Likewise, in an independent study, Molyneaux and Foster (2014) find the retail margin in VIC is higher than in NSW and QLD. For instance, the retail prices in NSW and VIC are about equal but the cost of distribution and transmission in VIC is much lower than in NSW. VIC should have the lowest cost network per capita in the NEM because VIC is the state with the highest population density in the NEM and a higher density population makes distribution and transmission relatively less costly, see Table 7. Therefore, using VIC to evaluate the efficacy of deregulation and privatisation is misleading unless VIC's naturally low network costs are considered. In this case, the retailers are absorbing the wind power induced decreases in wholesale spot prices with increases in profit margins.

Table 7: Population density by State in the NEM: a relative indicator of network costs

[Insert]

(Source: ABS 2015)

Nepal and Jamasb (2015) investigated privatisation and deregulation in the electricity industry finding reality falls short of the benefits promised and a more nuanced approach to development is required. They question the advocacy of following a one-size fits all plan in an idealised textbook theory of splitting the electricity industry into three segments: generation, network and retail, then privatising and deregulating. This process is supposed to engender competition and bring about price reductions. Ideally, competition to reduce prices occurs when there are numerous firms without the ability to exercise market power. Foster et al. (2013, sec. 10) discussed how the NEM compares to the market ideal and the prognosis for the NEM for increasing market power among the large retailer-generator companies who can leverage on their existing market power.

The Queensland Commission of Audit (QCA 2013, fig. 2) presents the ownership patterns in the NEM by indicative share. In the retail sector, three privately owned vertically integrated retail-generator companies, AGL, EnergyAustralia and Origin Energy own over 70% of the entire retail market and nearly 90% of the private market. This equates to considerable market power.

In the generation market, the same three retailer-generator companies own about 64% of the private market but since 2013 AGL bought Delta & MacGen from the NSW Government. This takes the same three retailer-generators market share of the private sector to 68%. These three retailer-generators are well positioned to buy the remaining state owned generation assets. Without intervention, the situation will develop where the market power by the big three retail-generation companies will become similar to the market power exerted by Woolworths and Coles within the Australian supermarket sector.

We could define the "market" as both generation and retail sectors. In which case, splitting the vertically integrated retail-generator companies into separate retail and generation companies would reduce market share and enhance competition.

In comparison, the whole transmission and distribution system is a natural monopoly but the NEM has 25 Network Service Provide (NSP) (AER 2016a) across 7 legislative jurisdictions supporting only 19 million residents (AEMO 2016b). In contrast, South Korea has a single NSP supporting 51 million residents. The 25 NSPs in the NEM serve to duplicate overheads and fail to provide any competition to reduce prices. Furthermore, natural monopolies allow for economic rent seeking; under government ownership this provides revenue for the Government for redistribution but under private ownership the proceeds of the economic rent merely concentrates wealth among the management and shareholders of the NSPs. Foster et al. (2013, sec. 10) and Bell et al. (2015a) discuss the

NEM's multiple NSP problem in more detail.

The three privately owned retail-generators companies, AGL, EnergyAustralia and Origin Energy that dominate the retail and generation markets are also Australia's first, second and third highest emitters of carbon dioxide, respectively (CER 2016) because they are the largest owners of fossil fuel generators. This poses a conflict of interest issue for these retail-generators because wind power is reducing the wholesale spot market prices, so reducing the profits of their large fossil fuel fleets. In a further conflict of interest, any new wind project (or any other new renewable project) would usually require a Power Purchase Agreement (PPA) with one of the three retail-generator companies before the project could obtain financing from banks. Thus, the willingness of the three above retail companies to write PPAs that might adversely affect the profitability of their own fossil fuel generation fleets can seriously affect (1) the development of renewable energy projects in the NEM and (2) the policy objective of combatting adverse climate change consequences by de-carbonising the electricity generation sector.

Additionally, the fossil fuel divestment movement is gaining pace both internationally and within Australia. These three companies will be potentially targeted for divestment. Divestment sends a message that burning fossil fuels is unethical, undermines the share value of fossil fuel companies and compromises their ability to finance any further development.

If Australia is to privatise and deregulate the retail electricity sector further to maintain downward pressure on retail prices, it makes sense to split the fossil fuel generators from the retail-generation companies beforehand for four reasons:

- to improve competition within both the retail and generation sectors,
- to prevent cross-subsidy between the retail sectors and fossil fuel generators,
- to make the retail sector less vulnerable to fossil fuel divestment, and
- to reduce the market power of those fossil fuel companies with potential conflict of interest with wind power.

5.4 'Gold-plated' State networks and interconnectors as hosepipes

The previous section discussed the uncongested intrastate transmission lines and the congested interstate transmission lines inducing a price islanding effect for each state. This observation supports Garnaut's (2011, p. 2) claim regarding inadequate interconnector capacity and 'gold-plated' state networks. Nunn (2011) differs with Garnaut's (2011, p. 38) assessment on underinvesting in interconnectors and gold plating intrastate transmission. Nunn (2011) asserts that the solution to increase the capacity of the interconnectors offered by Garnaut (2011, p. 38) implies a *"pipeline congestion"* view where interconnectors are bottlenecks. Using transmission binding constraint data, Nunn (2011) demonstrates that transmission network bottlenecks occur well before the pipeline limit, concluding any part of the network can affect interconnector flows. Nunn (2011) studies the frequency of the binding constraints and finds these binding constraints move around the network over time implying that there lacks an obvious solution. Empirical research from the National Electricity Market Management Company (NEMMCO) also shows that congestion tends to be transitory and influenced significantly by network outages (AEMC 2008, p. viii). However, NEMLink (AEMO 2010a, 2010b, 2011a, 2011b) being a high capacity backbone through the NEM, in which both the interconnectors and connecting intrastate transmissions form a part, resolves both the interconnector 'pipeline congestion' view and bottlenecks occurring deeper in the network. Moreover, neither NEMLink (AEMO 2010a, 2010b, 2011a, 2011b) evaluations assess congestion patterns and market benefits associated with significant penetration of wind power or other forms of renewable generation, instead being based largely upon the business as usual fossil fuel generation structure.

5.5 Developing transmission to new wind resources

An AEMC (2008, p. iv) report made a recommendation to "clarify and strengthen the Rules governing the rights of generators who fund transmission augmentations as a means of managing congestion risk, so that in the future connecting parties make a contribution to those funded investments from which they will benefit". This recommendation leaves the interconnector used by many generators in an overtly complex situation, so favouring intrastate investment over interstate. Concurring, Turvey (2006) analysis of interconnector economics finds interconnectors increase welfare but there is great uncertainty in their benefits and consequently in attributing these benefits to a NSP. Multi-interconnector and multi-NSP situations compound the attribution of benefits problems; the NEM has 8 interconnectors and 25 NSP comprising 8 Transmission NSP (TNSP), 14 Distribution NSP (DNSP) and 3 combined TNSP and DNSP (AER 2016a). Note Northern Territory and Western Australia networks are separate from the NEM.

The analysis by Turvey (2006) regarding the attribution of benefit problem to multi-NSPs would also apply to generators. For instance, when deploying the optimal size of transmission to new locations suitable for clusters of wind farms over who pays and who benefits. Furthermore, future generations will benefit from these long-term investments in transmission to new renewable sites, providing an intergenerational aspect. This justifies long-term loans to finance transmission projects. There was a precedent set by State Governments in the past that funded the transmission infrastructure for the existing coal fleet.

The current RIT-T arguably puts the consideration of new transmission to sites suitable for renewable energy beyond its procedures given its prime focus upon new investments to meet peak demand. Incorporating economic viability tests for sites suitable for renewable energy requires incorporating this aspect into the RIT-T. Such a change would align RIT-T with the broader government policies of addressing climate change. Foster et al. (2013, sec. 10.1) further discuss the financing and conflict of interest issues.

Zhang et al. (2016) provided a coordinated power planning model for the integration of wind power generation, transmission augmentation and energy storage to minimise overall costs. However, the conflict of interest and the co-ordination overhead of multi-NSPs within the multi-jurisdictions of the NEM makes the gainful deployment of a coordinated power-planning model unpromising. There is strong justification to amalgamate the transmissions and distribution NSPs to reduce cost and coordination overheads. The South Korea model of a single company owning all the transmission and distribution both minimises cost and coordination overheads and reflects their single legislator. Arguably, Australia's federal system would better suit the transmission owned and administered by the Federal Government and the distribution owned and administered by their respective State Governments. However, Australia does have the precedent of two publically owned national networks. (1) The publically owned company Telstra that operated the national copper wire telecommunications system. The subsequently privatised Telstra failed to provide Australia with a high-speed broadband network. (2) To remedy this failure, the Federal Government formed the National Broadband Network Company to install a national fibre optic network. Since privatisation, the Telstra network has been plagued with reliability issues. Australia's experiment with privatising a national network has been unsuccessful. Arguably, Australia's numerous NSPs are a historical artefact of Australia's once separate and isolated electricity networks now connected in a single market, the NEM. The South Korean model for transmission and distribution ownership has many technical and economic merits including importantly much simpler coordination and the Federal Government has managed national natural monopoly networks more efficiently than the private sector.

5.6 Nodal pricing optimising transmission, storage and generation location

Neuhoff et al. (2013) discuss the advantages of nodal pricing or locational marginal pricing. One such advantage is the reflection of the cost of transmission congestion at each node in the network. The DC OPF technique used by Neuhoff et al. (2013) and this paper provides nodal pricing. Zhang et al. (2016) also use DC OPF to develop their coordinated power-planning model. Additionally, Australian Renewable Energy Agency (ARENA 2016) project 'Australia Renewable Energy Mapping Infrastructure' provides high resolution geographic information on available network capacity among other information for renewable energy generators, such as, solar and wind resources. Both the information provided by the ARENA (2016) project and coordinated power planning model by Zhang et al. (2016) would help investors optimally locate generation, energy storage, electric vehicle recharging stations (Ergon Energy 2016) and virtual networks (ARENA 2014; Ergon Energy 2015) provided there are associated nodal price signals to guide the investment. However, the NEM currently uses pricing by state, which hides the price signal for the optimal locations. There is strong justification for the NEM to move to nodal pricing. This justification becomes stronger as the mix of renewable energy increases and with the imminent large-scale deployment of energy storage and eVs.

5.7 Using unregulated transmission as a congestion solution

AEMO (2015) discussed how there are two types of interconnectors in the NEM: regulated and unregulated. Unregulated interconnectors require transmission and control infrastructure that is capable of generating dispatchable power flows. Currently in the NEM, only the three HVDC interconnectors have this capability: BassLink, MurrayLink and DirectLink. BassLink is unregulated and MurrayLink and DirectLink are regulated. The unregulated (or market) interconnector derives its revenue by trading on the spot market using arbitrage between regions, or by selling the rights to revenue traded across the interconnector. Unregulated interconnectors are not subject to the AER's regulatory test evaluation. In contrast, a regulated interconnector is subject to the AER's evaluation. Regardless of actual usage, the TNSPs that operate the regulated interconnectors receive fixed annual revenue based on the value of the asset set by the AER. The revenues are derived from electricity end-users in the form of network charges added to their invoices. Given the existing thermal capacities and pricing by state in the NEM, the operators of DirectLink and MurrayLink found the regulated option more profitable.

The unregulated interconnector has the benefit of capturing the full benefit from introducing energy storage that is both transmission investment deferment and arbitrage profit from time shifting. The transmission-energy storage combination also addresses the intermittency of renewable energy. This combined approach to both congestion and intermittency management is worthy of further investigation. The approach could be adopted for intrastate transmission if this unregulated combination proved successful for interconnectors. But this expansion to include AC transmission would require investment in control infrastructure and for the NEM to change from pricing by state to pricing by node for transmission-energy storage entities to capture the full arbitrage value and provide appropriate price signals. However, the economic rents derived would be advantageous for the unregulated TNSP but could prove suboptimal for the NEM. In addition, this approach provides the opportunity for unregulated TNSP to game play the market and use Enron tactics and ethics to extract further economic rent. Finally, the NEM's relationship with its only unregulated interconnector has been turbulent (ABC 2016c).

6 Conclusion

We find the average wholesale spot price for all nodes in the NEM decreases when wind power increases from Scenario A that is 'no wind power' to Scenario E that meets Australia's original 2020 LRET of 41 TWh. We find five main components of the NEM need to be addressed to ensure that the benefits of the merit order effect from wind generation and other forms of renewable energy flow through to the retail customer. (1) The amalgamation of the NEM's 25 NSPs would reduce coordination and cost overheads. (2) The separation of fossil fuel generation ownership from the retail-generation companies would improve competition within both the retail and generation markets and improve the effectiveness of the RET by removing the conflict of interest that may exist when retailers sign power purchase agreements with renewable energy generators. This separation would also prevent the retail arm of a retail-generation company from passing-on non-RET compliance fines to the retail customers while the generation arm continues to profit from fossil fuel generation. (3) Additionally, legislative change would be required to remove a serious flaw in the current LRET arrangements that relate to the ability of retail companies to pass on the cost of penalty provisions associated with their own LRET non-compliance to their retail customers. (4) Adopting locational marginal cost pricing or nodal pricing would promote the optimal investment in generation, energy storage, virtual networks and eV recharging stations and help to defer investment in transmission and distribution. (5) Implement a high capacity transmission backbone to the NEM that would help to solve both the intermittency problems associated with renewable energy and reduce spot prices across the NEM.

We find in Victoria, whose retail market is deregulated and privatised, that the retail margin has simply increased under deregulation absorbing any wholesale spot price decrease induced by wind power. Therefore, there is a requirement to strengthen competitive rules if the benefits of wind power are to flow through fully to retail customers. Increasing competition would also mitigate carbon emissions by eliminating any cross-subsidy between the retail arms of vertically integrated retail-generator companies. The alternative to privatisation and deregulation is more enforceable and better regulation. We also find that wind power curtails wholesale spot price increases induced by demand growth and high gas prices (Bell et al. 2015b).

We find there is a need to address congestion on the interconnectors for wind power to induce further reductions in the NEM's average wholesale spot prices and carbon emissions. The average wholesale spot prices by node provide us with an alternative perspective on congestion discussed in Bell et al. (2015a). We find a single node's average wholesale spot prices can represent the majority of nodal' prices within each state and find price differentiation between states. These observations are consistent with Garnaut's (2011, p. 38) claim of gold-plating within state networks and underinvestment in interconnector capacity. We identify regulations that perpetuate this situation and require amendment.

There is also a potential conflict of interest between coal generators within each state and expanding interconnector capacity to states with surplus wind power. We also find a requirement to investigate the adequacy of the Regulatory Investment Tests for Transmission to allow the introduction of wind power in locations remote from the grid discussed in Section 5.5.

We find the 'Unrepresentative State Nodes' are clustered about two groups of interconnectors. The 'Unrepresentative State Nodes' are those that fail to follow price movements of the majority of other nodes within the state. Their location is consistent with interconnector congestion and the topology of these groups. The two groups are QNI-DirectLink and MurrayLink-NSW-VIC interconnections. The QNI-DirectLink grouping, see Figure 5, exhibits a complementary congestion pattern with increasing wind power due to single transmission line (Line 16) connecting the group to the rest of NSW. This unusual topology needs consideration in congestion solutions. The intrastate transmission is uncongested but Directlink requires augmenting. In contrast, the MurrayLink-NSW-VIC grouping is pivotal on Node 34 (Regional VIC), see Figure 6. This node has significant strategic value being the central hub in the NEM interconnector system; it connects VIC to both SA and NSW via MurrayLink and NSW-VIC (Tumut-Regional VIC) interconnector whose low thermal capacities 132 kV and 220 kV add to Node 34's sensitivity to congestion. Compounding its importance as a central and sensitive hub is its significance for wind power. Node 34 contains half of VIC's wind power and VIC, SA and NSW have the highest proportion of the NEM's wind power at the higher wind penetration scenarios considered. Increasing the capacity of MurrayLink and NSW-VIC (Line 37) would solve this congestion and facilitate wind power's integration into the NEM.

AEMO (2010a, 2010b, 2011a, 2011b) evaluated a proposed high capacity backbone to the NEM grid called NEMLink that would augment the existing transmission lines to address interstate congestion and enhance transfer capability; the NEMLink backbone includes Node 34, MurrayLink and NSW-VIC (Line 37). However, AEMO rejected NEMLink without considering higher penetrations of renewable energy. Bell et al. (2015c, 2015d) evaluated NEMLink and found that it would both ameliorate congestion and reduce wholesale spot prices under higher penetrations of wind power with the exception of DirectLink. Furthermore, the recent increases in retail prices induced by the combination of heavier reliance on more expensive OCGT generation (Apergis & Lau 2015) after the closure of the Northern and Playford B coal generators in SA (ABC 2016a) and of MurrayLink's low thermal capacity preventing the importation of cheaper fast ramping generations suggests a re-evaluation of NEMLink. NEMLink would address congestion in MurrayLink and beyond allowing the export of wind power from SA and faster ramping generation from outside of SA. NEMLink warrants revaluating with a range of LRET up to 100%. The higher deployment of variable renewable energy in Europe is also prompting re-evaluation of interconnector adequacy (Neuhoff et al. 2013; Spiecker, Vogel & Weber 2013).

Additionally, initial estimates of the cost of the six month long failure of the BassLink interconnector linking VIC and TAS vary widely from $180m (ABC 2016b) to $560m (Energy Quest 2016). This would also suggest reconsidering a second interconnector between VIC and TAS in a NEMLink re-evaluation. Any second interconnector would fall closer to SA. TAS contains most the of the NEM's hydro-generation. Benitez, Benitez and van Kooten (2008) discussed the many advantage of using hydro storage with wind power. Both Bell et al. (2015e) and Bannister and Wallace (2011) found the wind speed correlation between SA and TAS is relatively low at 0.24.

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Revitalising the wind power induced merit order effect (figures & tables)

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Figures

Tables

Figure 1: Topology of the states and interconnectors comprising the National Electricity Market

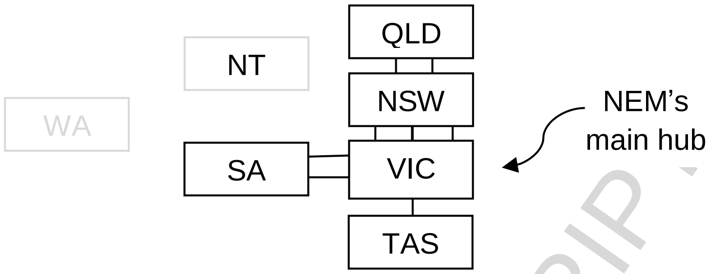


Figure 2: QLD average wholesale spot prices by node by projections years 2014 and 2025 and by weather baseline years 2010, 2011 and 2012

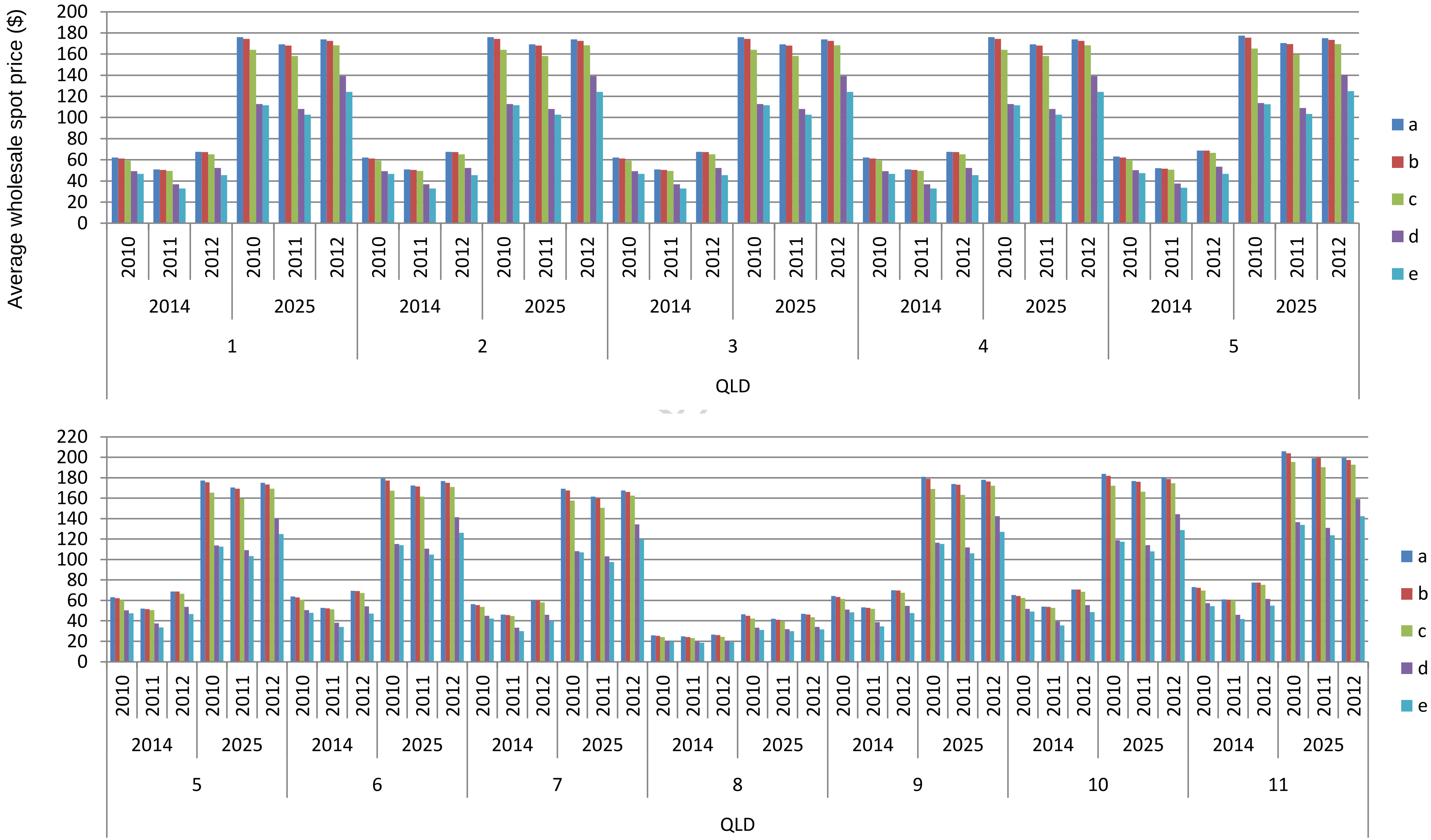


Figure 3: The representative nodes for each state in the NEM

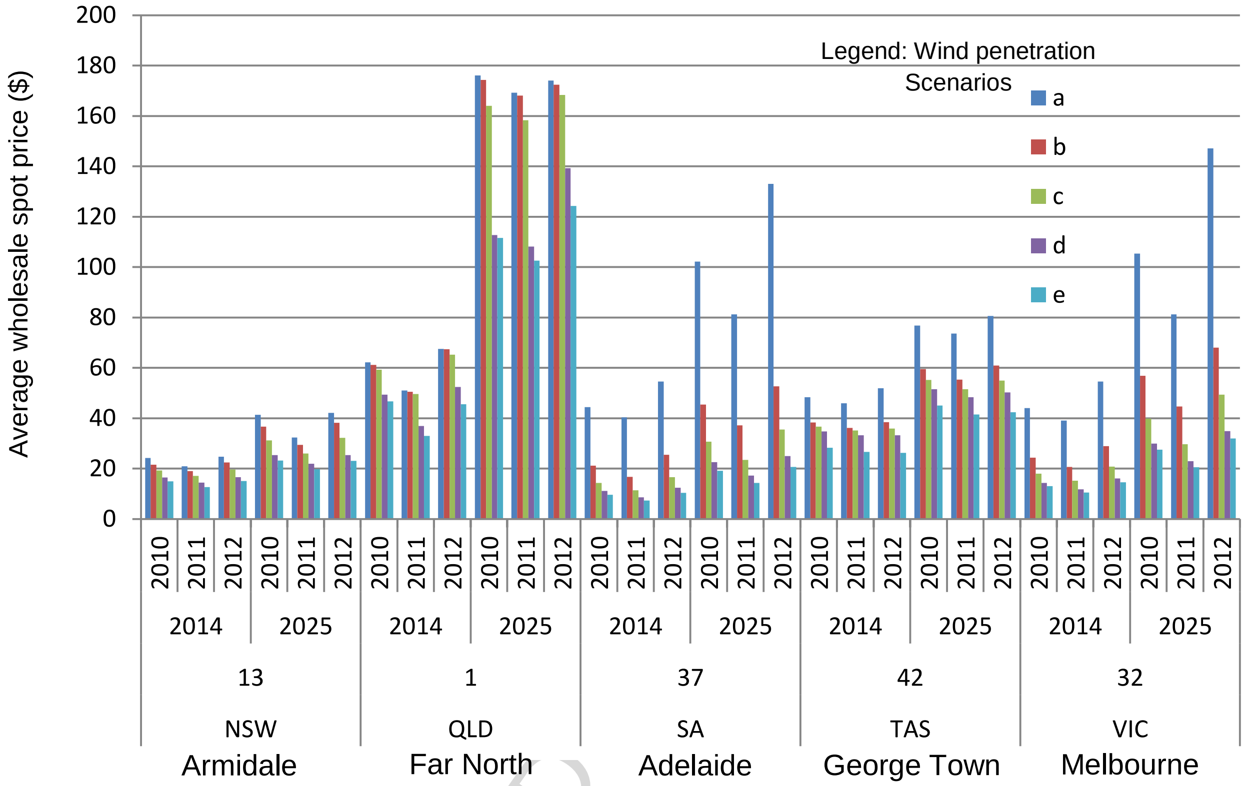
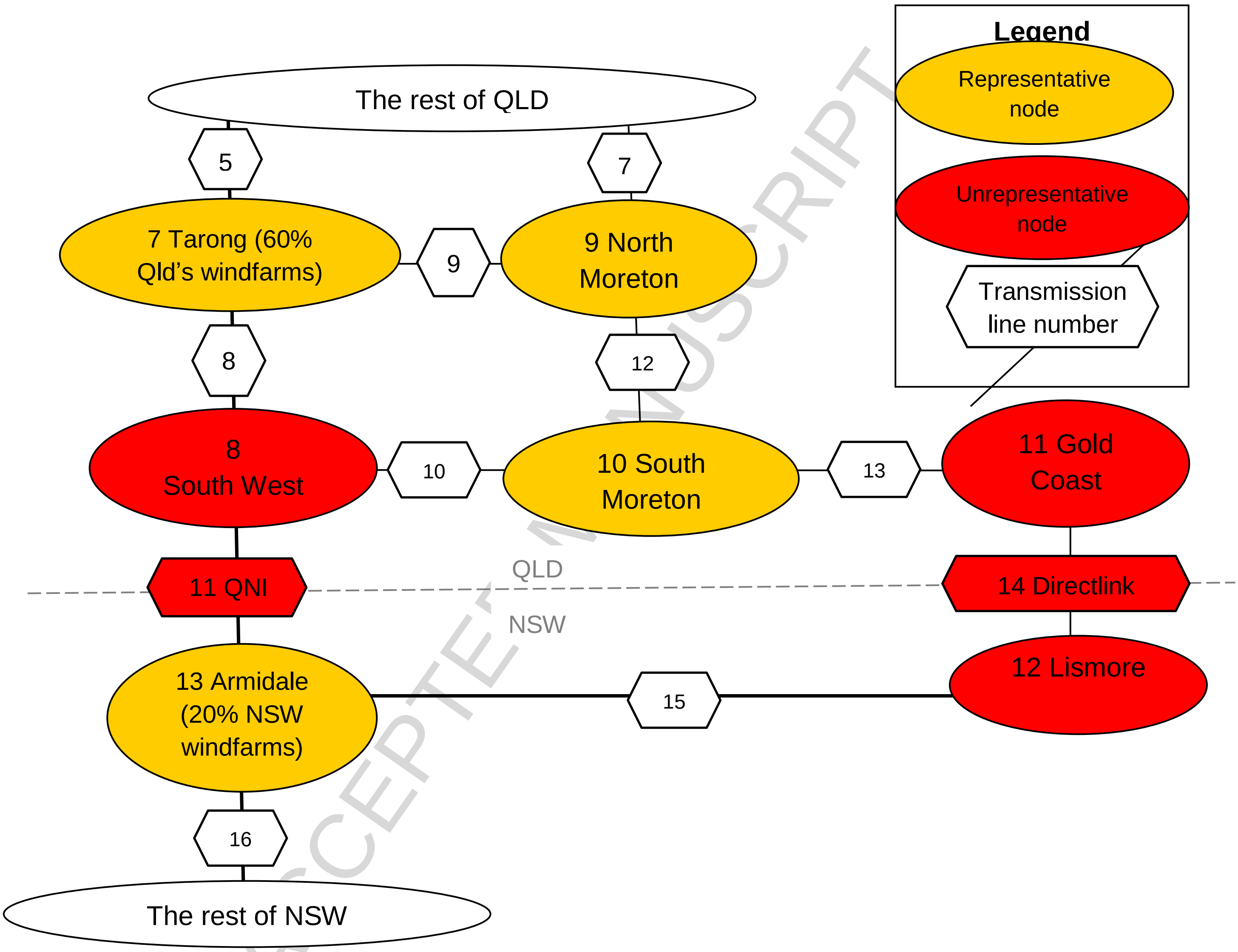


Figure 4: QNI and DirectLink Group



(Source: Wild et al. 2015, figs. 2 & 3)

Figure 5: QNI and DirectLink Interconnector terminal Nodes 8, 11, 12 and 13

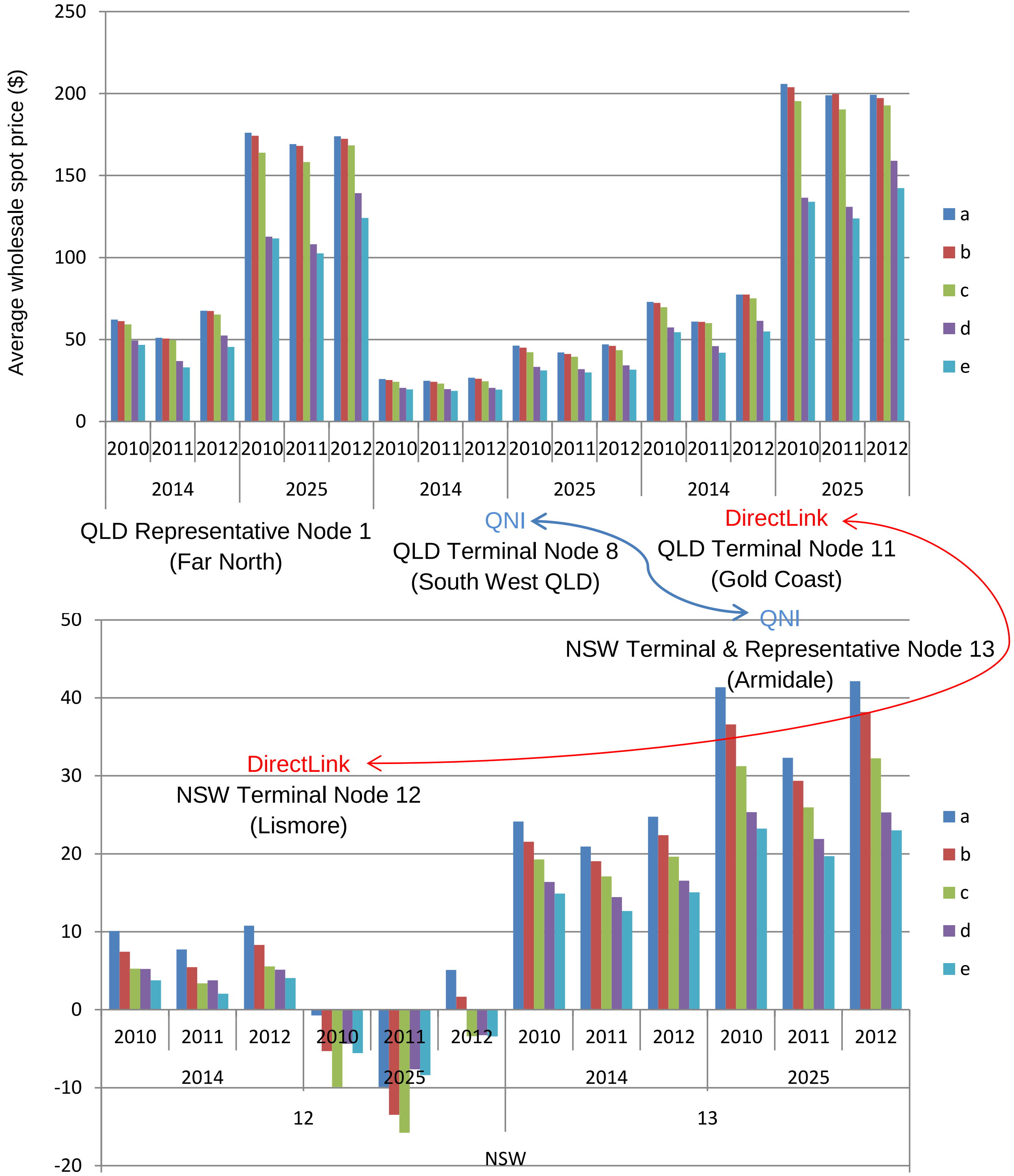
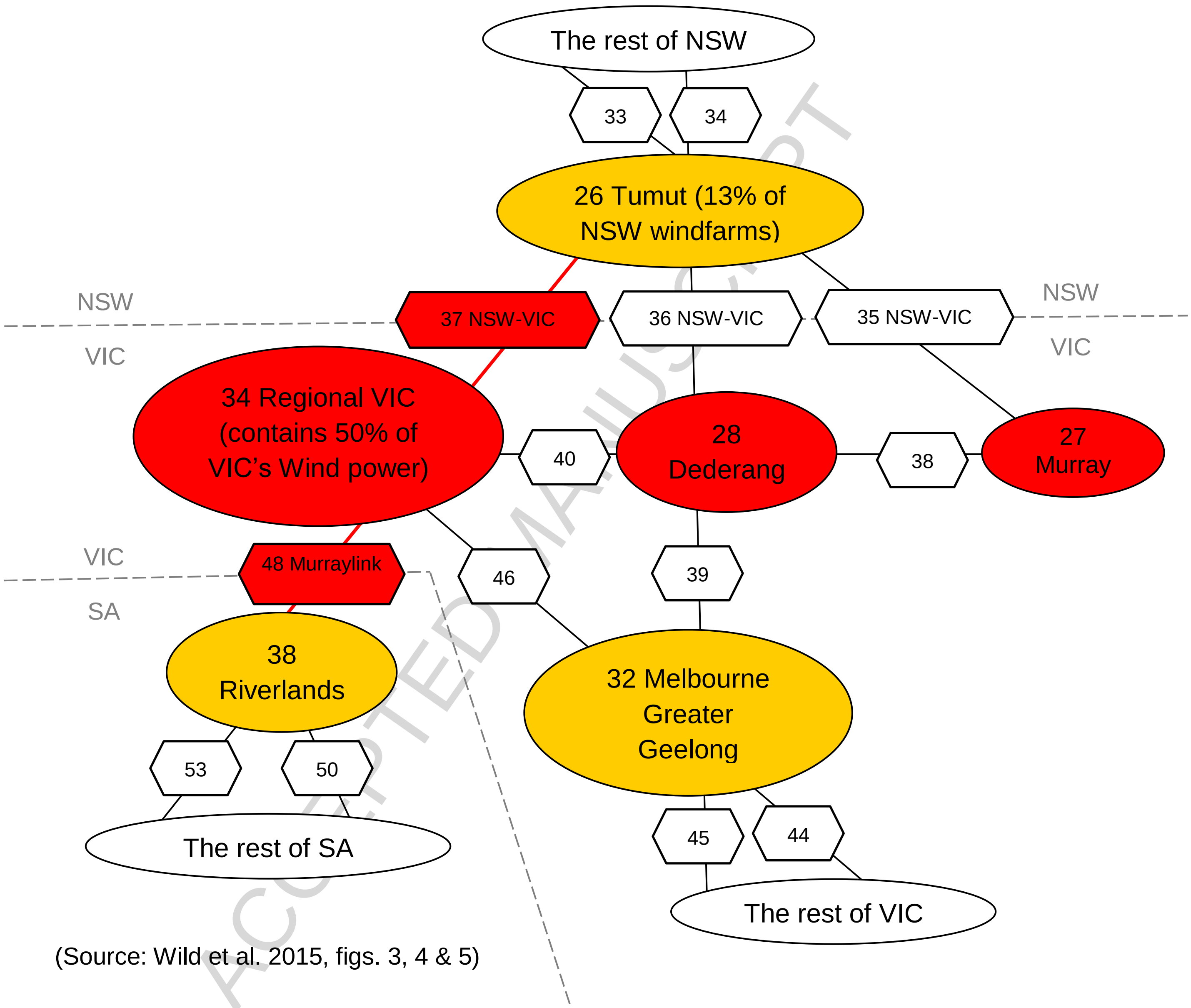


Figure 6: MurrayLink and NSW-VIC Interconnector terminal nodes



(Source: Wild et al. 2015, figs. 3, 4 & 5)

Figure 7: Benchmarking Unrepresentative VIC Nodes 27, 28 and 34 with Representative Node 32

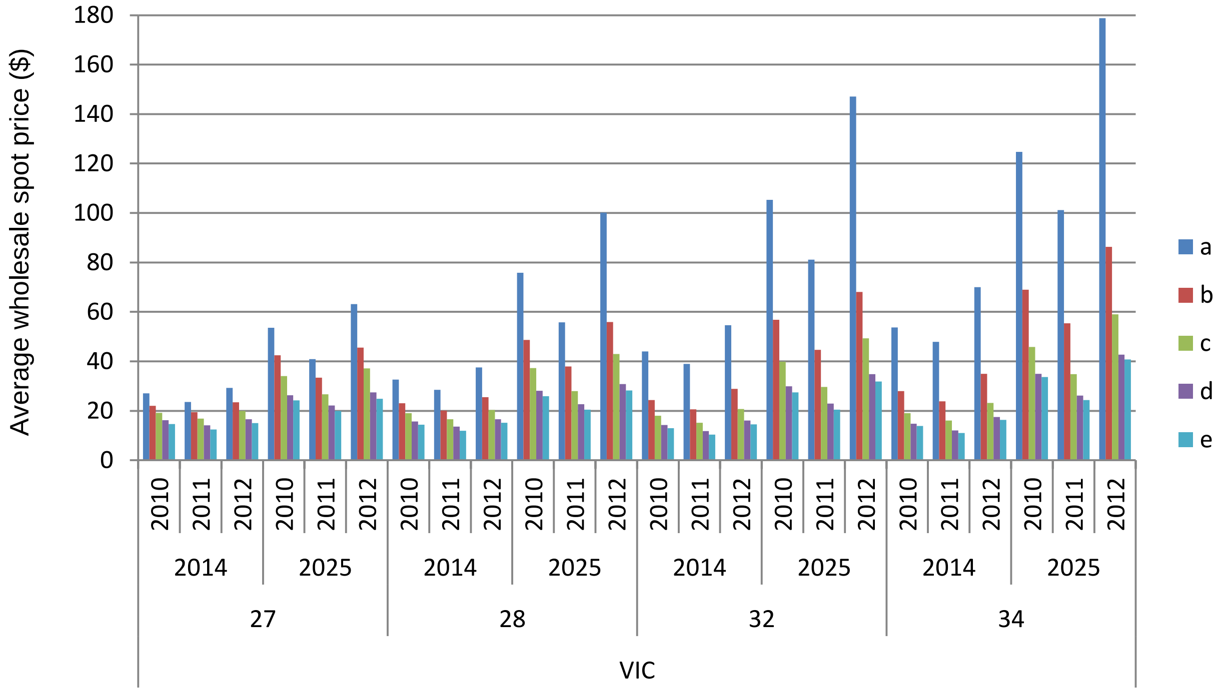


Figure 8: MurrayLink and NSW-VIC interconnector nodal price comparison

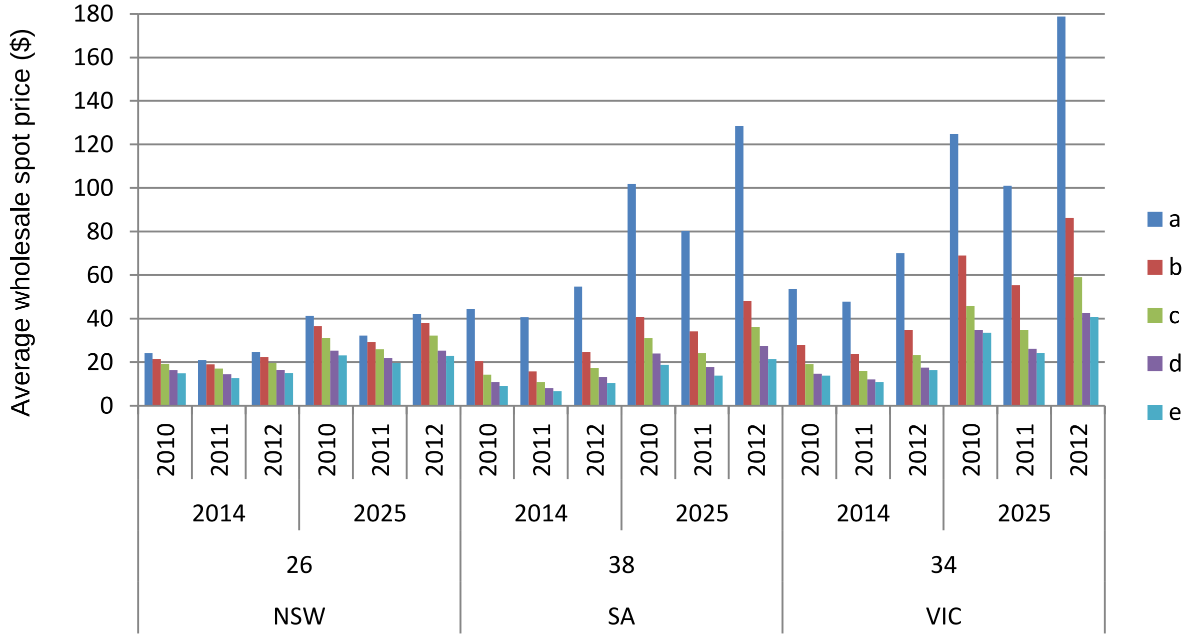


Table 1: NEM Windfarms by State and Scenario

State/Scenario	No of WTG	Capacity (MW)	Average Capacity Factor	Annual Production (GWh)
NSW	**1,670**	**4,517**	**0.38**	**15,001**
b	350	666	0.36	2,090
c	329	915	0.39	3,137
d	580	1,722	0.39	5,964
e	411	1,215	0.37	3,810
QLD	**328**	**936**	**0.41**	**3,497**
b	20	12	0.36	38
c	25	75	0.40	263
d	208	624	0.44	2,407
e	75	225	0.40	789
SA	**1,152**	**3,052**	**0.38**	**10,885**
b	649	1,473	0.36	4,883
c	193	579	0.41	2,149
d	134	402	0.43	1,522
e	176	598	0.44	2,331
TAS	**323**	**923**	**0.42**	**3,324**
b	118	308	0.42	1,134
d	45	135	0.42	492
e	160	480	0.40	1,698
VIC	**1,471**	**3,784**	**0.39**	**13,201**
b	592	1,223	0.38	4,072
c	415	1,245	0.40	4,401
d	464	1,316	0.40	4,728
Total	**4,944**	**13,212**	**0.39**	**45,907**

(Source: Wild et al. 2015, tbl. 5)

Table 2: QLD Windfarms by Node and Scenario

Scenario/Node	No of WTG	Capacity (MW)	Average Capacity Factor	Annual Production (GWh)
b	**20**	**12**	**0.36**	**38**
1	20	12	0.36	38
c	**25**	**75**	**0.40**	**263**
1	25	75	0.40	263
d	**208**	**624**	**0.44**	**2,407**
1	92	276	0.43	1,073
7	116	348	0.44	1,334
e	**75**	**225**	**0.40**	**789**
7	75	225	0.40	789
Total	**328**	**936**	**0.41**	**3,497**

(Source: Wild et al. 2015, tbl. 5)

Table 3: NSW Windfarms by Node and Scenario

Scenario/Node	No of WTG	Capacity (MW)	Average Capacity Factor	Annual Production (GWh)
b	**350**	**666**	**0.36**	**2,090**
20	15	10	0.34	30
23	132	277	0.36	890
25	203	379	0.37	1,170
c	**329**	**915**	**0.39**	**3,137**
13	25	75	0.39	256
21	33	99	0.40	346
23	46	138	0.36	438
25	141	351	0.37	1,145
26	84	252	0.43	951
d	**580**	**1,722**	**0.39**	**5,964**
13	293	879	0.39	3,009
20	106	318	0.40	1,105
21	38	114	0.35	350
23	35	105	0.36	334
24	18	36	0.39	124
26	90	270	0.44	1,043
e	**411**	**1,215**	**0.37**	**3,810**
21	288	864	0.36	2,687
24	123	351	0.38	1,123
Total	**1670**	**4,517**	**0.38**	**15,001**

(Source: Wild et al. 2015, tbl. 5)

Table 4: SA Windfarms by Node and Scenario

Scenario/Node	No of WTG	Capacity (MW)	Average Capacity Factor	Annual Production (GWh)
b	**649**	**1,473**	**0.36**	**4,883**
35	135	325	0.32	921
37	23	35	0.30	91
39	423	978	0.40	3,487
41	68	136	0.32	384
c	**193**	**579**	**0.41**	**2,149**
39	193	579	0.41	2,149
d	**134**	**402**	**0.43**	**1,522**
39	75	225	0.43	842
40	59	177	0.44	681
e	**176**	**598**	**0.44**	**2,331**
37	176	598	0.44	2,331
Total	**1152**	**3,052**	**0.38**	**10,885**

(Source: Wild et al. 2015, tbl. 5)

Table 5: VIC Windfarms by Node and Scenario

Scenario/Node	No of WTG	Capacity (MW)	Average Capacity Factor	Annual Production (GWh)
b	**592**	**1,223**	**0.38**	**4,072**
30	70	140	0.38	476
33	280	685	0.38	2,264
34	242	399	0.37	1,332
c	**415**	**1,245**	**0.40**	**4,401**
33	98	294	0.41	1,053
34	317	951	0.39	3,348
d	**464**	**1,316**	**0.40**	**4,728**
32	9	27	0.40	94
33	240	644	0.41	2,367
34	215	645	0.40	2,268
Total	**1471**	**3,784**	**0.39**	**13,201**

(Source: Wild et al. 2015, tbl. 5)

Table 6: TAS Windfarms by Node and Scenario

Scenario/Node	No of WTG	Capacity (MW)	Average Capacity Factor	Annual Production (GWh)
b	**118**	**308**	**0.42**	**1,134**
44	62	140	0.41	501
46	56	168	0.43	633
d	**45**	**135**	**0.42**	**492**
42	12	36	0.43	137
45	33	99	0.41	355
e	**160**	**480**	**0.40**	**1,698**
50	160	480	0.40	1,698
Total	**323**	**923**	**0.42**	**3,324**

(Source: Wild et al. 2015, tbl. 5)

Table 7: Population density by State in the NEM: a relative indicator of network costs

State	Population 2014 Sept.	Estimated Area (km2)	Density of Population People per square kilometre
NSW	7,544,500	800,642	9.4
QLD	4,740,900	1,730,648	2.7
SA	1,688,700	983,482	1.7
TAS	515,000	68,401	7.5
VIC	5,866,300	227,416	25.8

(Source: ABS 2015)

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Highlights

- Strong wind power induced merit order effect in Australia's National Electricity Market
- Need high capacity backbone to overcome congestion on 6 interstate transmission lines
- Lack of competition hindering merit order benefits passing to consumers
- Need to split the large generator-retail companies to increase competition
- Current regulations and institutions unsuitable for increasing wind power